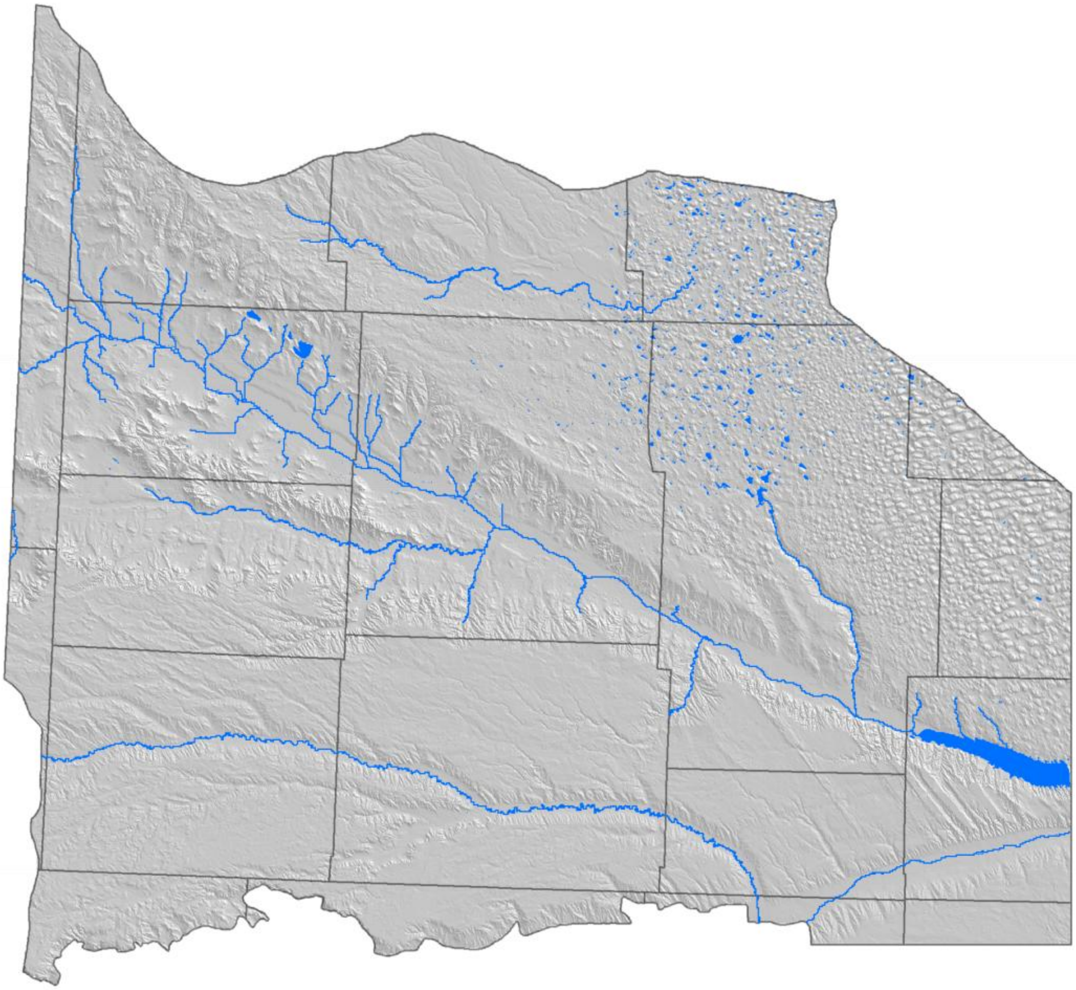
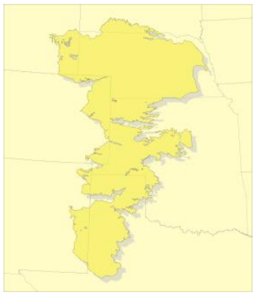
Ground Water Flow Model for the Southern Half of the Nebraska Panhandle





Prepared by
Richard R. Luckey
High Plains Hydrology, LLC

for

North Platte Natural Resources District
South Platte Natural Resources District
and
Nebraska Department of Natural Resources

June 2013

Contents

Page

Page

Page

Figures

Tables

Introduction

The Nebraska Panhandle covers the area of Nebraska west of approximately 102º longitude (fig. 1). This is a semi-arid area with average annual precipitation of about 17 inches (Luckey and Cannia, fig. 5) and average annual potential evapotranspiration of about 49 inches (Dugan and Zelt, fig. 17). This is predominately an agricultural area that includes dryland and irrigated crops as well as extensive grasslands.

North Platte Natural Resources District, South Platte Natural Resources District, and Nebraska Department of Natural Resources started a study of the water resources of the southern two-thirds of the Nebraska Panhandle in 2009. The study was called the Western Water Use Management Model study. This water-resources study was divided into three parts: a regionalized soil-water balance model, a surface-water operations model, and a ground-water flow model. The ground-water study was built on the earlier Cooperative Hydrology Study, which was a hydrologic study of surface water and ground-water resources of the Platte River basin upstream of Columbus, Nebraska. This study covers the western model unit of the Cooperative Hydrology Study area. This is the report of the ground-water flow model built as part of the water-resources study.

Natural resources districts were established in Nebraska in 1972 to conserve, protect, develop, and manage natural resources. They are governed by locally elected boards of directors and are primarily supported by local property taxes. Managing ground water is one of the responsibilities of natural resources districts.

Description of Study Area

The study area covers about 11,100 mi^2 in the southern two-thirds of the Panhandle of Nebraska (fig.1). The study area extends west to east from about 6 mi into Wyoming to Kingsley Dam on Lake McConaughy. The study area's southern boundary along the western end of the study area extends about 14 mi into Colorado in order to reach the southern extent of the High Plains aquifer in that area. Further east, the study area extends 6 mi south into Colorado in Sedgwick County. The High Plains aquifer is described later in this report. The northern limit of the study area extends from one ground-water divide in Sioux County to another ground-water divide in Sheridan County and follows a ground-water flow line between the divides. Assuming that the northern boundary was correctly drawn, no ground water crosses the northern boundary.

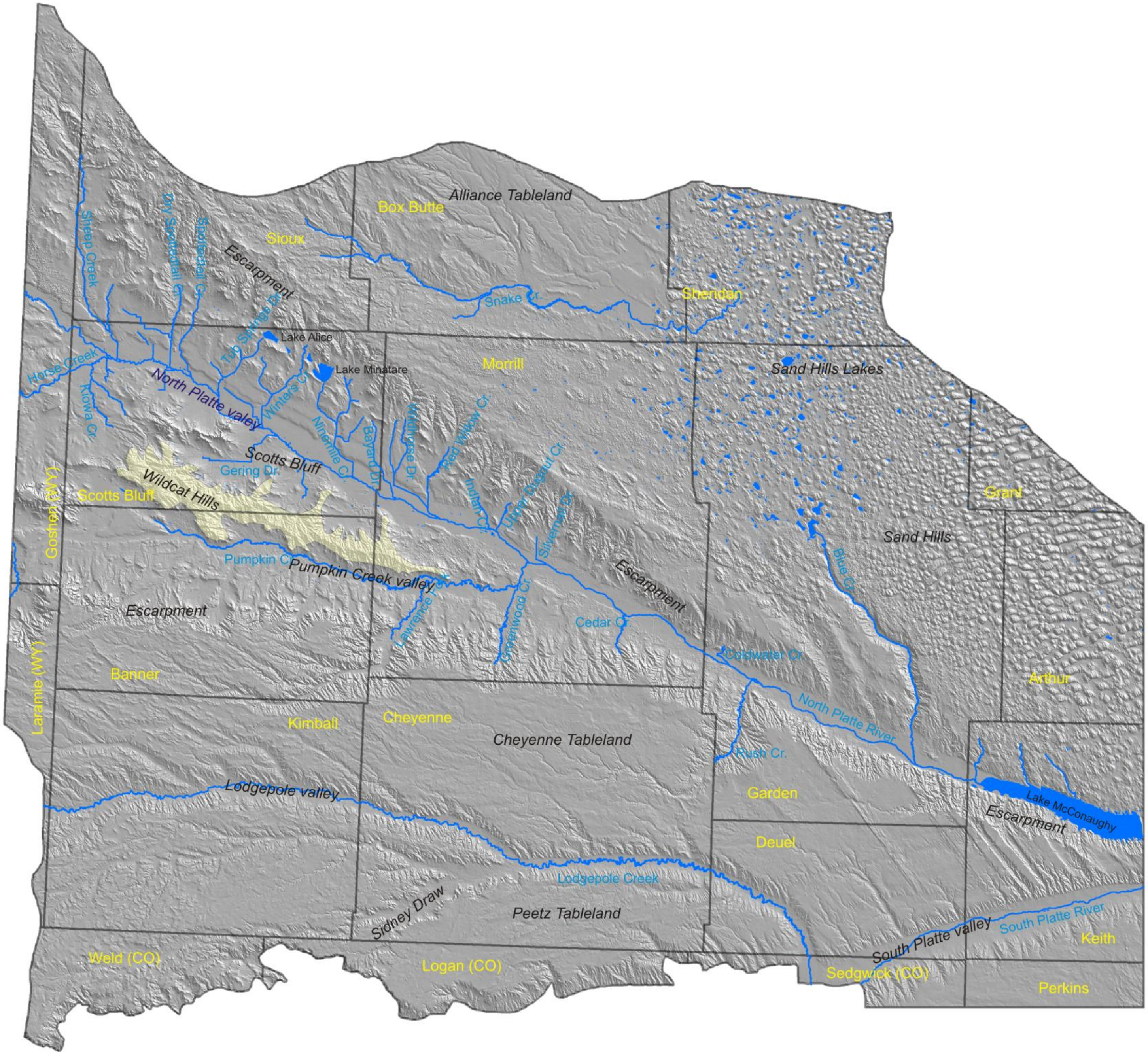


Figure 1. Study area, counties, major perennial streams and lakes, and selected features.

The study area boundaries were chosen to extend sufficiently beyond the boundaries of the North Platte Natural Resources District and South Platte Natural Resources District that errors in estimated flows across the boundaries or estimated water levels at the boundaries should have minimal effect on the ground-water system within the districts.

Figure 1 shows the major features within the model area. The North Platte River, South Platte River, and Lodgepole Creek are the major surface-water features draining the area. The North Platte River has numerous tributaries, especially in the western part of the study area where surface-water has long been diverted to irrigate crops. The South Platte River and Lodgepole Creek do not have any perennial tributaries in the study area.

The land surface in the study area ranges from over 5500 ft above sea level in the southwest part of the study area in Weld County, Colorado, to less than 3200 ft above sea level in the South Platte valley at the eastern edge of the study area. Locally in Scotts Bluff County, altitude ranges from over 4800 ft in the Wildcat Hills to less than 3800 ft in the nearby North Platte valley. Altitude is more than 4600 ft at the top of Scotts Bluff National Monument and about 1 mi away it is 3900 ft in the valley. Land surface generally slopes to the east with a relief of about 19 ft/mi on the Cheyenne Tableland. Locally, land surface slopes toward the valleys with relief up to 200 ft/mi. Relief is also large in the Sand Hills where the tops of dunes may be more than 250 ft above the inter-dune areas.

The North Platte valley, including the topographic region called valley side slopes, covers about 1,400 mi^2 in the study area. The South Platte valley covers about 100 mi^2 in the southeastern corner of the study area and Lodgepole Creek valley and its tributary Sidney Draw covers about 300 mi^2 . Pumpkin Creek valley covers about 600 mi^2.

The forested Wildcat Hills (about 200 mi^2) separate the North Platte valley from Pumpkin Creek valley. The former is widely irrigated with surface water while the latter is almost entirely irrigated with ground water. Further south is a broad tableland broken by Lodgepole Creek valley. Parts of the tableland and the valley are irrigated with ground water. The tableland, called the Cheyenne Tableland, covers about 3,000 mi^2, of which about 1,900 mi^2 is north of Lodgepole valley and about 1,100 mi^2 is south of Lodgepole valley. The southern part is sometimes referred to as the Peetz Tableland.

Another broad tableland north of the North Platte valley, called the Alliance Tableland, covers about 1,300 mi^2 in the study area and continues on north of the study area. East of the Alliance Tableland is the Sand Hills, which cover about 2,600 mi^2 in the study area. This is only a small part of the 19,300 mi^2 Sand Hills.

Scottsbluff is the largest town in the study area with a population of 14,372 in 2000. Nearby Gering had a population of 7,751. Alliance is the second largest town in the study area with a population of 8,959. Sidney, in the southern part of the study area had a population of 6,280 and Ogallala, in the eastern part of the study area, had a population of 4,930. Other towns in the study area with a population over 1,000 were Kimball (2,559), Mitchell (1,831), Bridgeport (1,594), Julesburg, Colorado (1,467), and Bayard (1,247). Torringrton and Pine Bluffs (both inWyoming) are larger towns just outside the study area.

Precipitation ranges from less than 14 in/yr on the western part of the study are north of the North Platte River to more than 18 in/yr on the eastern part of the study area. Precipitation generally increases from west to east and generally decreases from higher areas to lower areas. The study area is part of Nebraska Climate Division 1. The 1895-2010 average precipitation for Climate Division 1 was 17.26 in/yr and ranged from 9.95 in/yr in 2002 to 27.67 in/yr in 1915. About two-thirds of the annual precipitation falls during the irrigation season of May through September.

Purpose and Scope of Report

This report covers the general characteristics of the ground-water flow system and documents a numerical model constructed to simulate the flow system. The report covers model construction and calibration, but does not cover use of the model to manage the ground-water system.

Previous Studies

Luckey and Cannia (2006) previously described this study area and much of this section is repeated directly from that report. The earliest studies of ground water in western Nebraska were done by Darton (1899, 1903, and 1905). Meinzer (1917) did a brief investigation of Lodgepole Creek Valley and Bjorklund (1957) did a more extensive study of the area. Cady and Scherer (1946) did the first of several studies of Box Butte County. Later studies of Box Butte County included those of Nace (1953), Souders and others (1980), and Pettijohn and Chen (1984). Wenzel and others (1946) studied Scotts Bluff County, Babcock and Visher (1951) studied the Dutch Flats area, and Babcock and Visher (1952) studied the Pumpkin Creek valley, which is predominately in Banner and Morrill Counties. Bjorklund and Brown (1957) studied the South Platte valley. Smith (1969) studied Cheyenne County, Smith and Souders (1971) studied Kimball County, and Smith and Souders (1975) later studied Banner County.

Large area studies after the Darton (1905) study began with the Missouri River Basin Commission (1975). This was later followed by the Missouri Basin States Association (1982a and 1982b). A study of the entire High Plains aquifer was reported by Gutentag and others (1984) and Weeks and others (1988). Pettijohn and Chen (1983a and 1983b) did more detailed reports on the Nebraska portion of this study of the High Plains aquifer. Conservation and Survey Division (1998) did a report on the ground-water resources of the entire state of Nebraska. Stanton and others (2011) prepared water budgets for the entire High Plains aquifer.

More recent ground-water studies in the North Platte valley include those of Steele and others (1998), Verstraeten and others (2001), and Steele and others (2002). These studies covered only small parts of the study area.

Studies of canal bed sediments and canal leakage potential include Kress and others (2004), Ball and others (2006), Burton and others (2009), and Vrabel and others (2009).

Studies of western Nebraska that included a ground-water flow model or other detailed numerical analysis include Missouri River Basin Commission (1975), Lappala and others (1979), Missouri Basin States Association (1982a and 1982b), Pettijohn and Chen (1984), Luckey and others (1986), McLean and others (1997), Luckey and Cannia (2006), Ayers (2007), Peterson and others (2008), and Stanton and others (2010).

Studies of the geology of western Nebraska of particular importance to the current study include Swinehart and Diffendal (1997) and Swinehart and others (1985).

Land-use studies were published for 1982 (Dappen and Merchant, 2004), 1997 (Dappen and Tooze, 2001), 2001 (Dappen and Merchant, 2003), and 2005 (Dappen and others, 2006).

Testhole descriptions have been published for most of the counties in the study area. These include Arthur County (Diffendal and Goeke, 2000), Banner County (Smith, 2000a), Box Butte County (Smith, 2000b), Cheyenne County (Diffendal, 2000), Deuel County (Diffendal, 1999), Garden County (Smith and Swinehart, 2000), Keith County (Diffendal and Goeke, 2004), Kimball County (Smith 2000c), Morrill County (Souders and Swinehart, 2000), Perkins County (Dreeszen, 2000), and Scotts Bluff County (Sibray and Smith, 2000).

Concurrent Studies

This report is part of the Western Water Use Management Model project supported by North Platte Natural Resources District, South Platte Natural Resources District, and Nebraska Department of Natural Resources. The project is under the overall direction of Thad Kuntz (Adaptive Resources, Inc.). This report covers only the ground-water flow model portion of the project.

Adaptive Resources, Inc. (Thad Kuntz) is in the process of writing an overall project summary and the report will be titled "Western Water Use Management Model Summary, Goals, and Documentation." Also the documentation for the modeling data integration and calibration plan was completed in February 2013 and titled "DRAFT WWUM Modeling Data Integration and Calibration Plan."

Wilson Water Group (Kara Sobieski) is in charge of the surface-water management model portion of the project. Among other things, they are responsible for estimating recharge due to canal and lateral leakage, recharge due to surface-water application, and supplemental pumpage on surface-water parcels. The surface-water management model was undergoing final calibration as this report was completed. The plan is to document the surface-water management model, but no such documentation has yet been completed. Reports currently produced include "Western Water Use Management Model Historical Crop Consumptive Use Analysis" (Draft dated June 2013).

Leonard Rice Engineers, Inc. (Mark Mitisek and Shane Michael) is in charge of land use mapping in support of this project and merging of pumpage and recharge data sets for the ground-water model. The land use mapping provides part of the basis for pumpage and recharge estimates for the ground-water model. The land use mapping report covers irrigated and dryland parcels, including crop type, for 1953-2010. For irrigated parcels, it also includes water source and application method. The work includes shapefiles for dryland parcels, irrigated parcels, and irrigation wells for each year from 1953 through 2010. Reports currently produced include "Western Water Use Management Model Irrigated and Dryland Acreage Assessment" (May 2012) and "WWUM_Canal_Recharge_05162013.pdf" (May 2013). Data sets currently produced include "LRE_WWUM_Comingled_Pumping_Recharge_ 05172013.zip" (various comingled pumpage and recharge data sets), "WWUM2012.ddh" (monthly diversion information for the North Platte valley), "PmpCrk2012.ddh" (monthly diversion information for Pumpkin Creek valley), "Western2012.ddh" (monthly diversion information for Western Canal), "WWMU_Final_Cell_Conveyance_Loss_05162013.txt" (monthly canal loss by ground-water model cell), "WWMU_Final_Structure_Conveyance_Loss_05162013.txt" (monthly canal loss by canal or part of canal), "FarmHGDeliv_TFG.stm" (monthly farm headgate deliveries for the North Platte valley), and "WWMU_Conveyance_Loss_Factors_09062012_Final.shp" (canal conveyance loss factors by ground-water model cell).

The Flatwater Group (Marc Groff, Shane Dolph, and Isaac Mortensen) is in charge of estimating net irrigation requirement and deep percolation (surrogate for recharge) throughout the study area. They also estimate ground water irrigation efficiency to produce gross ground water irrigation pumpage for the ground-water model. They also produce recharge from precipitation for 1953-2010 for the ground-water model. They estimate the fate of runoff from fields to apply part of that back to recharge. Most of this is accomplished using a regionalized soil-water balance model. The plan is to document the regional soil-water balance model, but the documentation has not yet been produced. Working title of the document is "The Western Water Use Model: Regionalized Soil Water Balance Model." The plan also is to produce individual data sets for net irrigation requirement, gross irrigation pumpage, and deep percolation, but the data sets have not yet been produced.

Nebraska Department of Natural Resources (Jesse Bradley) is in charge of producing baseflow estimates at streamflow gages to be used as targets in the ground-water model. The report "Hydrograph Separation Methods Used to Estimate Groundwater Discharge for Assistance in Calibration of the Western Water Use Model" was in review as this report was completed. Appendix A of that report will provide the data, but it is not yet in review. However, spreadsheets containing the data were provided earlier for use in the ground-water model.

Adaptive Resources, Inc. (Thad Kuntz) is in charge of producing water-level elevations to be used as targets in the ground-water model. "DRAFT – Technical Documentation of the Development of Water Level Calibration Targets" was in review as this report was completed, but it did not contain the data. However, text files containing the data were provided earlier for use in the ground-water model.

Acknowledgements

This study was supported by Nebraska Department of Natural Resources, North Platte Natural Resources District, and South Platte Natural Resources District. Thanks to Brian Dunnigan, Director of Department of Natural Resources, and his staff, particularly Jesse Bradley, Doug Hallum (now with University of Nebraska, Conservation and Survey Division), and Rick Vollertsen. Also thanks to Ron Cacek, manager of North Platte Natural Resources District, his board of directors, and his staff, particularly Thad Kuntz (now with Adaptive Resources, Inc.). Also thanks to Rod Horn, manager of South Platte Natural Resources District, his board of directors, and his staff.

This study was conducted by a number of different people from several different entities. The study was under the overall direction of Thad Kuntz (Adaptive Resources, Inc., formerly with North Platte Natural Resources District). The surface-water operations model was constructed by Kara Sobieski (Wilson Water Group, LLC, formerly with Leonard Rice Engineers, Inc.). The ground-water flow model was constructed by Richard Luckey (High Plains Hydrology, LLC). The regionalized soil-water balance model was run by Marc Groff (The Flatwater Group, Inc.), aided by Isaac Mortensen and Shane Dolph. Land use mapping was done by Mark Mitisek and Shane Michael (Leonard Rice Engineers, Inc.). Stream-

baseflow targets were generated by Jesse Bradley (Nebraska Department of Natural Resources) and water-level targets were generated by Thad Kuntz. Streamflow and water-level hydrographs were made using a program created by Rick Vollertsen (Nebraska Department of Natural Resources).

Geology and Hydrology of the Area

This section gives a brief overview of the geology of the area, particularly as related to the ground-water flow system. This section then gives a somewhat broad overview of the hydrology of the area. The Conceptual Flow Model section then gives more details about the ground-water flow system in the area.

Geologic History

The geologic history of the study area that is important to this study begins late in the Cretaceous Period with the Laramide Orogeny. This was a period of mountain building in western North America that began 70-80 million years ago (MY) and ended 35-55 MY. These mountains were eroded about as fast as they were formed (Gutentag and others, 1984) and by the middle of Oligocene time were virtually peneplained. Meanwhile, extensive volcanism was occurring west of the study area, which provided much of the source material for the Chadron Formation, Brule Formation, and the Arikaree Group.

Another period of mountain build occurred about 5-28 MY. This started in Oligocene time and continued through Miocene time. This episode provided much of the material for the Ogallala Group, which is primarily a braided stream deposits of sediments originating in the Rocky Mountains. The climate during this time was wetter and warmer than the present climate (Gutentag and others, 1984, p. 13).

The mountains again rose during Pliocene time and sediments from these mountains provided the source material for the Broadwater Formation. By this time, the modern drainage system in the study area was established (Condon, 2005, fig. 16).

The alluvial material in the river valleys probably were deposited, eroded, and redeposited several times during the Quaternary Period. Terraces along the North Platte River are of both Pleistocene and Holocene age (Condon, 2005, p. 47). The dunes in the Sand Hills may have been active late into the Holocene, although they may have been formed earlier.

Geologic Units

Figure 2 shows the generalized geology of the study area and table 1 gives information on the geologic units. Cretaceous age rocks underlie the study area, but do not crop out in the study area, except for the Fox Hills Sandstone in the extreme western part of the area. These rocks are too deep to affect the flow system discussed in this report.

The Chadron Formation of Eocene age underlies the study area (Condon, 2005, fig. 12) but is generally too deep to be used as a water supply in the study area. Only a few wells in the North Platte valley use water from the Chadron Formation.

The Brule Formation of Oligocene age also underlies the study area and outcrops in Lodgepole valley, its tributary Sidney Draw, Pumpkin Creek valley, at the base of Wildcat Hills, and along the margins of the North Platte valley. Generally the Brule Formation is a massive siltstone that transmits little water and forms the base of the High Plains aquifer. However, in some areas it is highly fractured or contains channel deposits, yields large amounts of water to wells, and is considered part of the High Plains aquifer. This primarily occurs in Lodgepole valley, Sidney Draw, and Pumpkin Creek valley. In these areas it is usually overlain by a veneer of alluvium, which supplies the fractures with water. Fractured Brule Formation also occurs in some places in the North Platte valley and is used if another source of water is not available. The occurrence of fractures in the Brule Formation is seemingly random and difficult to predict, although they occur more often along the centers of the valleys.

The Arikaree Group of Miocene and Oligocene age underlies the northwestern part of the study area and outcrops on the Wildcat Hills. It also has limited occurrence south of Pumpkin Creek valley. It was probably removed by erosion from Pumpkin Creek valley and North Platte valley. It is generally a fine grained material but can yield substantial amounts of water to wells when it has extensive thickness. It is the only source of water on the Wildcat Hills and in the northwestern part of the study area.

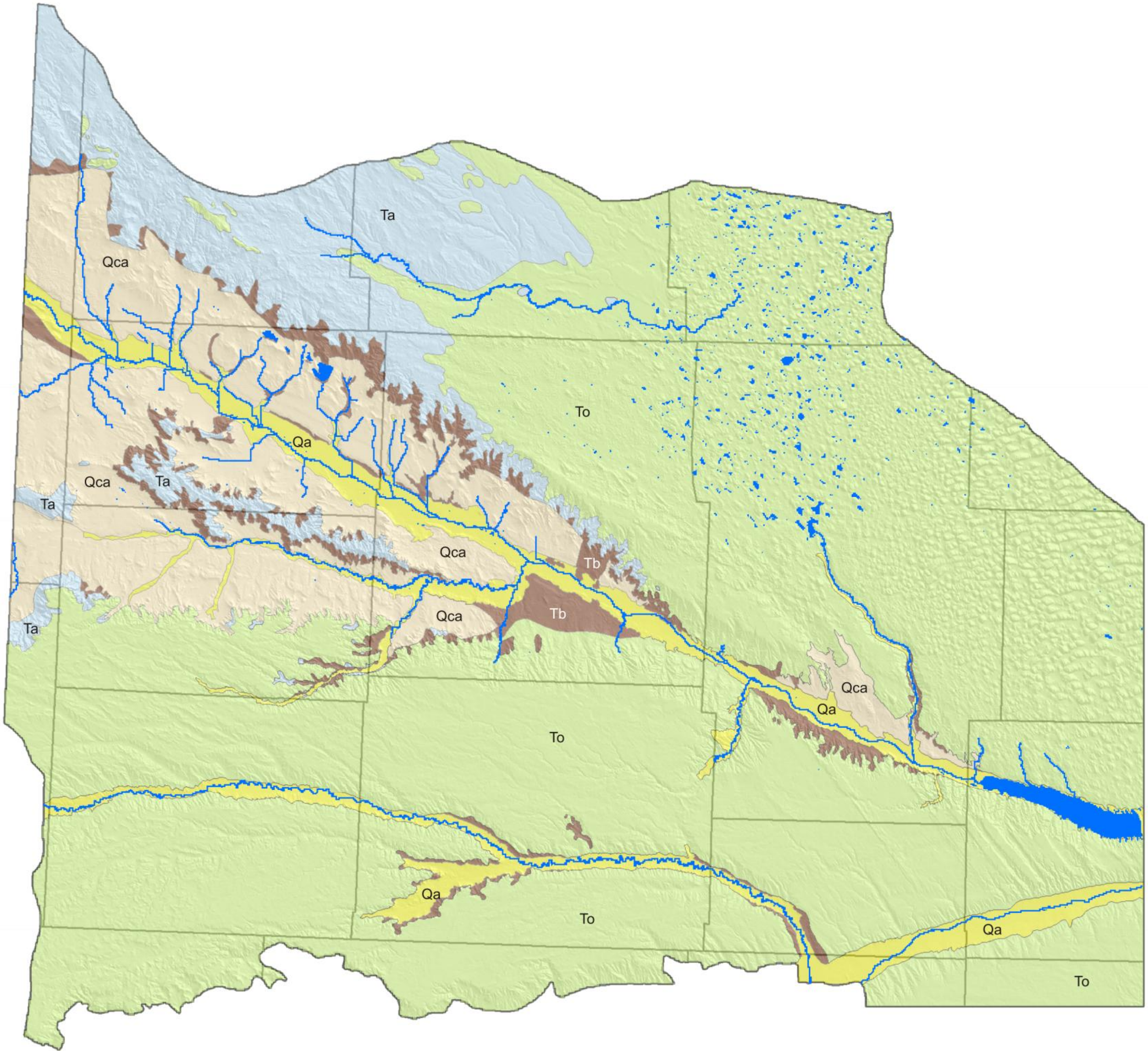


Figure 2. Generalized geology of the study area. Modified from Conservation and Survey Division (1996) and Swinehart and Diffendal (1997). Qa is alluvium; Qca is collumium and alluvium; To is Ogallala Group; Ta is Arikaree Group; and Tb is Brule Formation.

Table 1. Generalized section of geologic units in western Nebraska (modified from Gutentag and others, 1984 and Luckey and Cannia, 2006).

System	Series	Geologic unit	Description
Quaternary	Holo-cene	Alluvium and colluvium	Gravel, sand, silt, and clay with coarser materials more common. Generally fluvial deposits. Occurs in major river valleys where it can be over 150 feet thick.
	Pleistocene and Holocene	Dune sand	Generally fine sand but may contain some medium and even coarse sand. May also contain some finer material. Eolian deposits. Thickness may exceed 300 feet in northeastern part of the study area, but much of this thickness is above the water table.
		Loess deposits	Generally silt, but may contain some very fine sand and clay. Deposited as eolian dust. Generally less than 20 feet thick, but may be more than 200 feet thick in southeastern part of the study area (Swinehart and Diffendal, 1997). Generally above the water table.
	Pleisto-cene	Alluvial deposits	Gravel, sand, silt, and clay with coarser materials more common. Generally fluvial deposits. Underlies alluvium and colluvium in places along North Platte River and Pumpkin Creek, where it is generally less than 100 feet thick.
Tertiary	Plio-cene	Broadwater Formation	Coarse gravel and sand with some silt and clay. Fluvial deposits. Generally found in channel deposits north of the North Platte. Occurs in northeast part of the study area where it can be over 150 feet thick, but much of this thickness is above the water table.
	Upper and middle Miocene	Ogallala Group	Heterogeneous mixture of gravel, sand, silt, and clay. Generally fluvial deposits but also contains eolian deposits. Upper part contains caliche caprock which forms the High Plains surface. Typically 200-400 feet thick, but may exceed 600 feet thick.
	Lower Miocene and upper Oligocene	Arikaree Group	Predominately very fine to fine-grained sandstone but may also contain siltstone. Eolian volcanic ash deposits. Locally, may contain conglomerates, gravels, and sands of fluvial origin. Occurs in northwestern part of the study area. Typically 200-400 feet thick, but may exceed 600 feet thick.
	Lower Oligocene	Brule Formation of White River Group	Predominately siltstone, but may contain sandstone and channel deposits. Sometimes highly fractured with areas of fracturing difficult to predict. Upper part of Brule Formation is included in High Plains aquifer only if fractured or contains sandstone or channel deposits, otherwise it is excluded from the High Plains aquifer. Eolian volcanic ash deposits with lacustrine and some fluvial deposits.
	Upper Eo-cene	Chadron Formation of White River Group	Silt, siltstone, clay, and claystone with minor amounts of sandstone. Generally forms impermeable base of High Plains aquifer. Fluvial deposits and eolian volcanic deposits. Some coarser fluvial deposits exist at the base of this unit.
Cre-tace-ous	Undif-feren-tiated	Undifferentiated	Shale, chalk, limestone, siltstone, and sandstone. Except for a few minor areas of Fox Hills Sandstone in the extreme western part of the study area, generally forms an impermeable base of High Plains aquifer. Deep marine deposits to beach deposits.

The Ogallala Group of Miocene age underlies and outcrops in much of the study area, except in the river valleys where it has been removed by erosion. It is composed of a complex sequence of gravels, sands, silts, and clays primarily laid down by fluvial processes. It has been aptly described as the garbage can for the Rocky Mountains. It yields large quantities of water to wells, both because of its coarser materials and its thickness. It is typically 200-400 ft thick, but is thicker in the northeast part of the study area.

The Broadwater Formation of Pliocene age caps some of the hills on the north side of the North Platte valley where the gravels armor the hills. This unit is generally above the water table. Condon (2005, fig. 16) shows a paleovalley filled with Broadwater rocks in the Cheyenne Tableland but this paleovalley was not found in this study.

Dune sand of Quaternary age is found primarily in the northeast part of the study area. Although these dunes can be thick, the bulk of them are above the water table. These dune sands comprise a major recharge area for the ground-water system described in this report.

Alluvium of Quaternary age is found primarily in the North Platte valley and South Platte valley but thinner deposits are also found in other valleys. The alluvium can yield substantial amounts of water to wells and is frequently the only source of water in the valleys.

Surface-Water Hydrology

The North Platte River drains the majority of the study area (fig 1). This river originates in Colorado and transverses Wyoming before it enters the northwest part of the study area. It is by far the largest stream in the study area in terms of its flow. One tributary, Horse Creek, originates in the Laramie Mountains of Wyoming. The rest of the North Platte River tributaries originate in the study area.

A number of tributaries enter the North Platte River from the north in the western part of the study area. These tributaries have considerable flow, primarily due to surface-water irrigation. These tributaries seldom flow north of the outer canals in the area.

Further downstream Pumpkin Creek is a southern tributary to the North Platte River from the south in Morrill County. This tributary drains a large area south of the Wildcat Hills, but it has little flow, especially since ground-water development began in the basin. Two smaller tributaries enter the North Platte River downstream from Pumpkin Creek from the south, Cedar Creek and Rush Creek. These tributaries have little flow except in their lowermost reaches.

Blue Creek is a north side tributary to the North Platte River in Garden County. This tributary drains the Sand Hills and has considerable year-around flow. Several smaller tributaries enter the North Platte

River from the north downstream of Blue Creek. These too drain the Sand Hills and have year around flow.

The South Platte River drains a minority of the study area and cuts across the southeastern part of the study area. This river originates in Colorado and joins the North Platte River east of the study area. It is considerably smaller than the North Platte River in terms of flow.

Lodgepole Creek is tributary to the South Platte River and joins it in Sedgwick County, Colorado, just outside the study area. Lodgepole Creek originates in the Laramie Mountains of Wyoming and enters the southern part of the study area. Lodgepole Creek always had little flow considering its drainage area and has had almost no flow since ground-water development began in the area.

Figure 3 shows the gages on streams that were active in 2009. Not shown in the figure are gages on canals. There are six gages on the North Platte River, including State Line, Mitchell, Minatare, Bridgeport, Lisco, and Lewellen. There are 11 gages on tributaries to the North Platte River, including Horse Creek, Sheep Creek, Dry Spottedtail Creek, Tub Springs Drain, Winters Creek, Gering Drain, Ninemile Creek, Bayard Drain, Red Willow Creek, Pumpkin Creek, and Blue Creek. There is one gage on Lodgepole Creek, which is above Oliver Reservoir. At one time there was another gage near the mouth of Lodgepole Creek. There is one gage on the South Platte River in the study area and another just east of the study area.

There are numerous canals that divert water from the North Platte River (fig. 4) and irrigate lands in the North Platte valley. The largest of these, Interstate Canal (Pathfinder Irrigation District) and Ft. Laramie Canal (Gering Ft. Laramie Irrigation District) divert in Wyoming and also irrigate lands in Wyoming. In addition to natural flow, these canals also receive storage water from large upstream reservoirs in Wyoming. Storage water means that these canals receive water even during dry years.

Mitchell Canal (Mitchell Irrigation District and Gering Irrigation District) and Tri-State Canal (Farmers Irrigation District and Northport Irrigation District) are large canals that divert from the North Platte River near the state line. These canals also receive storage water from upstream reservoirs.

Further downstream numerous smaller canals divert water from the North Platte River. These range from the 38 mi Belmont Canal (Bridgeport Irrigation District) to the 3 mi Short Line Canal. Some, but not all of the smaller canals receive storage water.

Several canals divert water from Pumpkin Creek and its tributary Greenwood Creek. These are small canals, some of which are no longer active. Two canals on Greenwood Creek divert several hundred acre-feet of water per year.

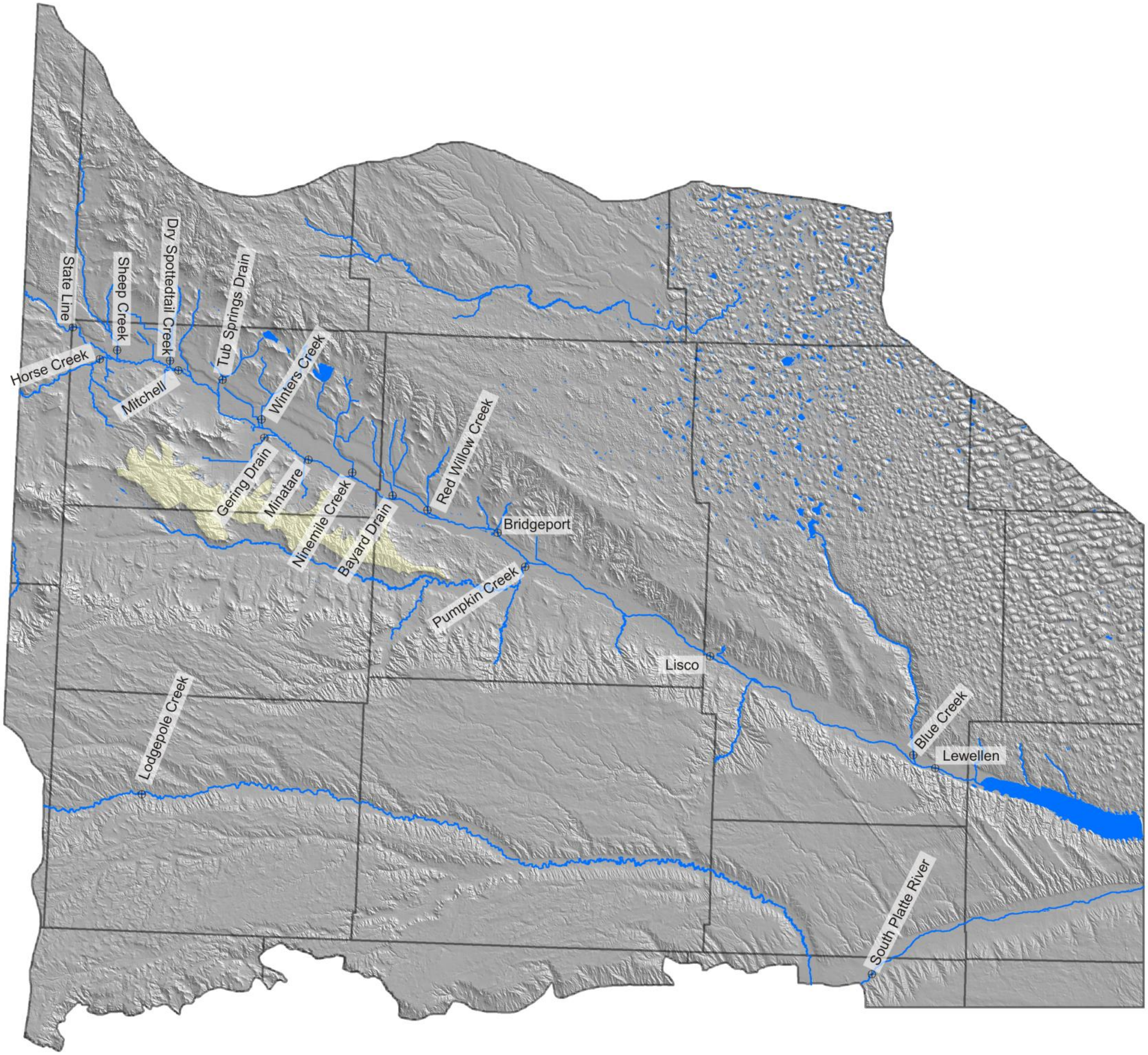


Figure 3. Stream gages active that were active in 2009.

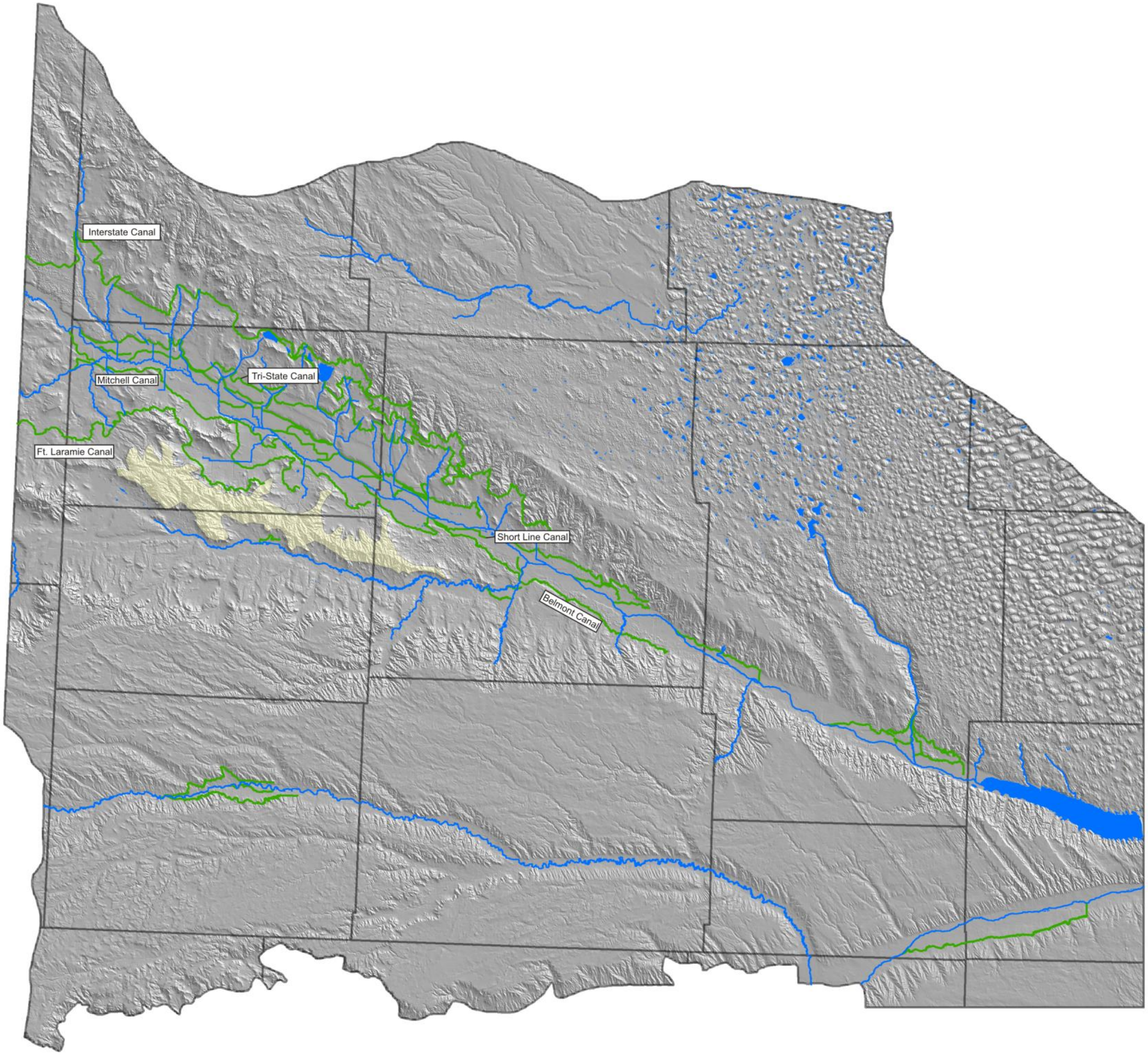


Figure 4. Canals in the study area.

Four small canals divert water from Blue Creek. These canals only irrigate land in Blue Creek valley and the nearby North Platte valley.

Western Canal is a large canal that diverts water from the South Platte River in the study area. This canal irrigates about 10,000 acres.

A number of canals diverted water from Lodgepole Creek, with the largest being South Kimball Canal and North Kimball Canal. None of the canals along Lodgepole Creek are active anymore.

Ground-Water Hydrology

The High Plains aquifer is the principal aquifer in the study area. It is composed of the saturated portions of fractured Brule Formation, Arikaree Group, Ogallala Group, Broadwater Formation, and various sediments of Quaternary age, principally alluvial deposits in the major valley. Throughout most of the study area only a single unit exists in the High Plains aquifer. There may be Arikaree Group beneath the Ogallala Group in much of the study area and there is Ogallala Group beneath alluvium in the South Platte valley. However, in these cases the upper unit typically yields sufficient water that the lower unit is generally not used.

Potentiometric Surface

The potentiometric surface is the upper limit of the High Plains aquifer (fig. 5). Ground-water flow is perpendicular to the contours shown in the figure. The potentiometric surface ranges from over 5400 ft above sea level in the southwestern part of the study area to less than 3200 ft in the South Platte valley in the eastern part of the study area. In the southern part of the study area the potentiometric surface slopes from west to east with a smaller gradient toward Lodgepole Creek and the South Platte River. There is a steep gradient to the north from the Cheyenne Tableland into Pumpkin Creek valley. Within Pumpkin Creek valley, the potentiometric surface slopes toward the creek and toward the east. Further north, the potentiometric surface is highest in the Wildcat Hills and slopes away from this highland area in all directions. In the North Platte Valley, the potentiometric surface slopes toward the river and toward the east. On the Alliance Tableland, the potentiometric surface slopes generally to the east, but there is a strong southward gradient along the escarpment between the Alliance Tableland and the North Platte valley. In the northern part of the Sand Hills, the potentiometric surface is relatively flat and in the southern part it slopes toward Blue Creek and the North Platte River.

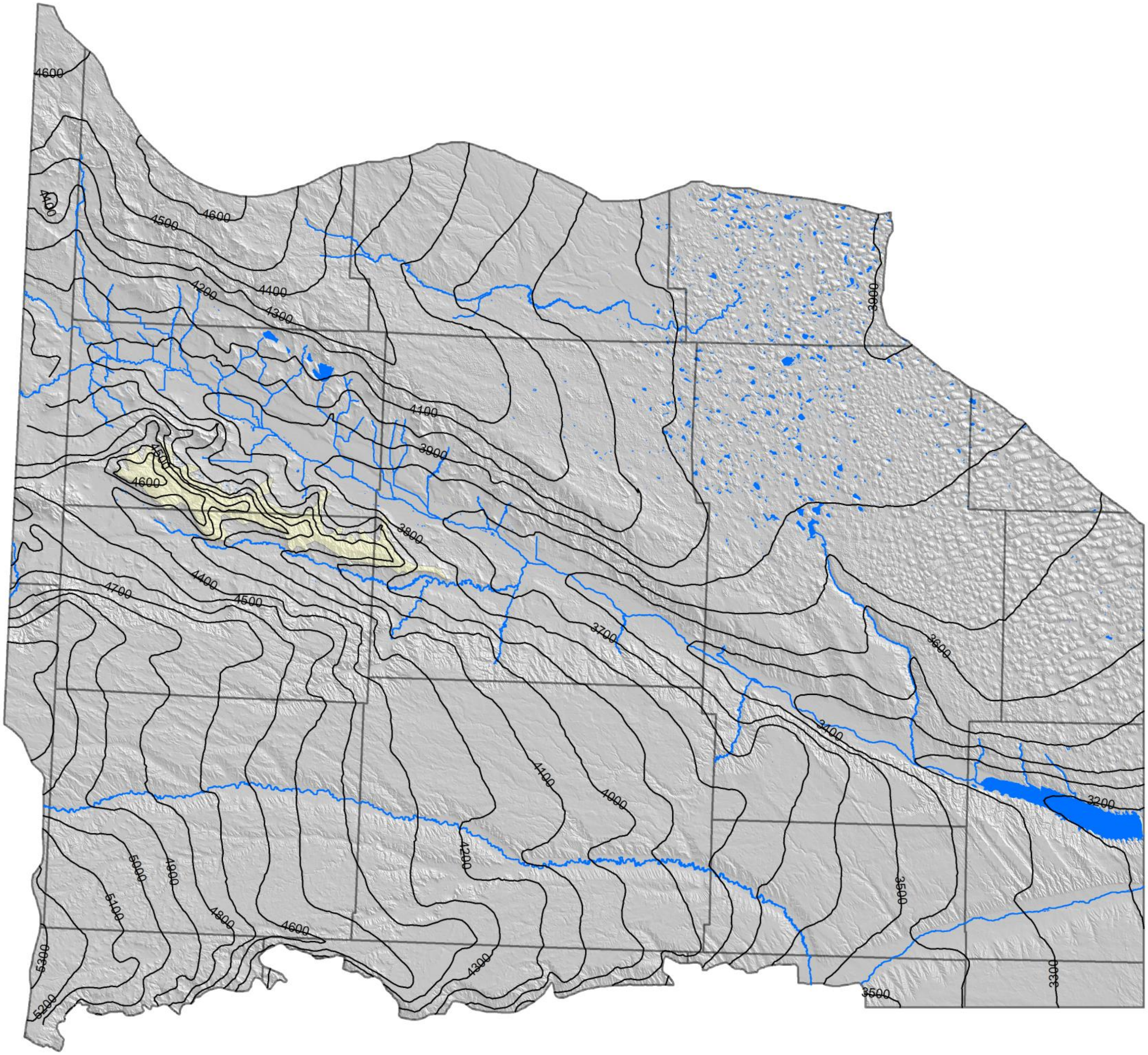


Figure 5. Pre-ground-water development period potentiometric surface (from Gutentag and others, 1984). Contour interval is 100 ft. Datum is sea level.

The potentiometric surface has a high of over 4600 ft at a ground-water divide in Sioux County and water flows southwest, south, and southeast from this high. The northern boundary of the study area follows a ground-water divide along this high. Inside the study area, flow from the western and southern part of the divide is to the southwest toward Sheep Creek and other tributaries to the North Platte River. Flow from the eastern part of the divide is toward the east.

The potentiometric surface has a high of over 3900 ft along a ground-water divide in Sheridan County and water flows away from this high. The boundary of the study area here follows the boundary of the previous model (Luckey and Cannia, 2006), which is somewhat west of the ground-water divide. Water flows to the west and south from this divide, although the gradients are small as shown by the large spacing between the potentiometric surface contours.

The complex contours in southern Scotts Bluff County and northern Banner County and extending into Morrill County are due to the Wildcat Hills. The gradients are large in this area but the aquifer is thin, so the flow out of this area is small. Ground-water flow is north to the North Platte River and its tributaries and ground-water flow is south to Pumpkin Creek.

The potentiometric surface contours veer strongly upstream along most of the North Platte River, indicating that ground-water flow is toward the North Platte River and its valley. The contours are closely spaced in central Morrill County along the northern edge of the North Platte valley, indicating a large gradient in the potentiometric surface. The aquifer is thin along this edge of the valley, so flow into the North Platte valley is small. The contours are also closely spaced in southern Garden County along the southern edge of the North Platte valley. The aquifer is also thin along this edge of the valley, so flow into the North Platte valley is small.

Ground-water Flow Direction

Figure 6 shows the direction of flow of ground water in the High Plains aquifer. Ground-water flow is perpendicular to the potentiometric surface, so this figure tells the same story as the previous figure. In the Cheyenne Tableland, flow is generally from west to east with a smaller component of flow toward Lodgepole Creek and the South Platte River. There is flow from the Cheyenne Tableland into Pumpkin Creek valley, but small saturated thickness along the escarpment limits this flow. Flow in Pumpkin Creek valley is toward the creek, and to a lesser extent, toward the east. In the North Platte valley, flow is toward the river or towards streams tributary to the river. On the Alliance Tableland, flow is toward the east or southeast, although locally it is toward Snake Creek. In the northern part of the Sand Hills flow is complex as water moves away from a ground-water divide along the northeastern part of the study area.

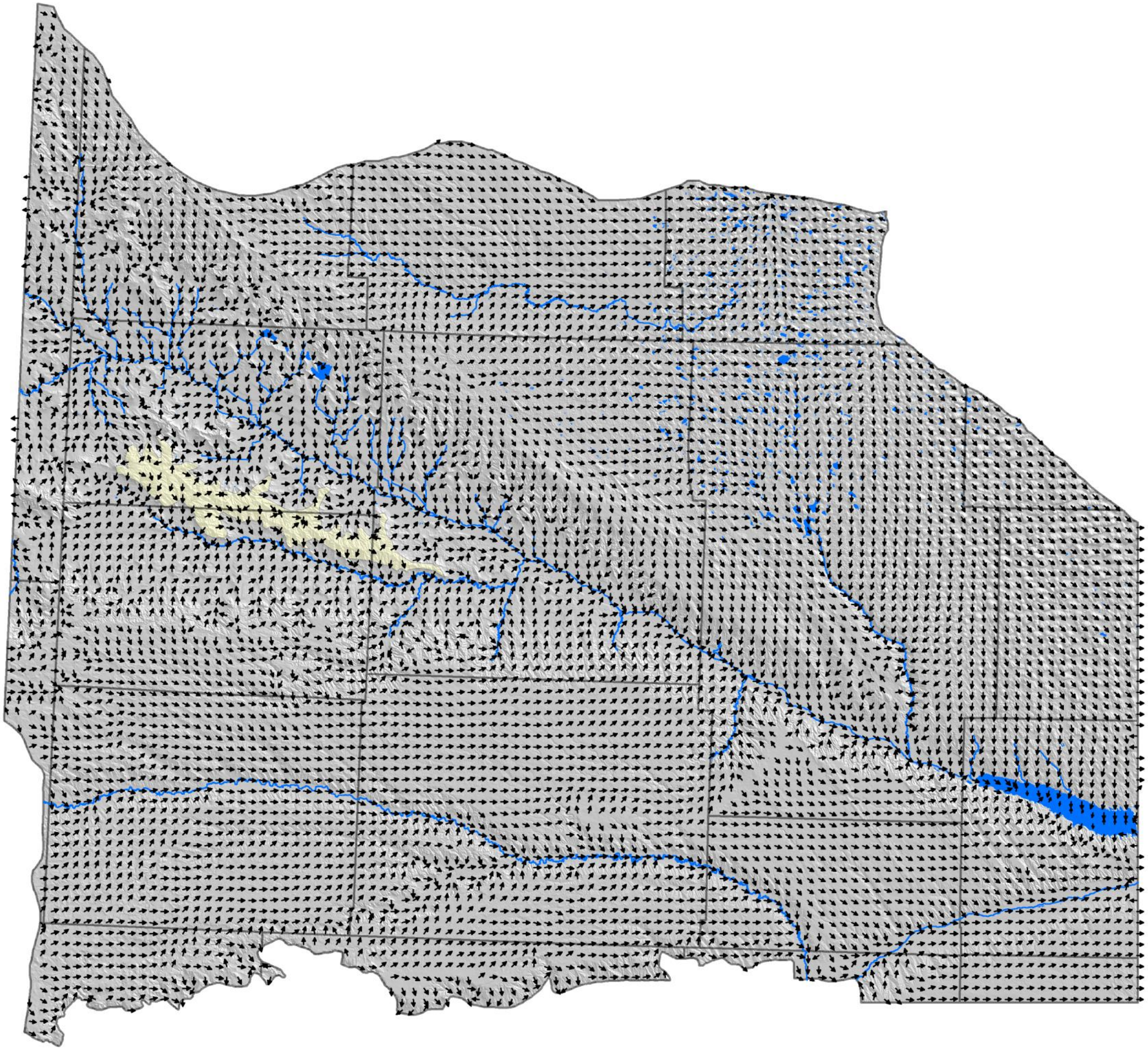


Figure 6. Direction of ground-water flow in the High Plains aquifer.

However, the amount of flow in this area is small because the potentiometric surface is relatively flat. Further south in the Sand Hills flow is toward the south or toward Blue Creek.

Saturated Thickness

Figure 7 shows the saturated thickness of the High Plains aquifer. Saturated thickness ranges from essentially zero to over 800 ft. The largest saturated thickness occurs in the Sand Hills along the eastern boundary of the study area. Data are sparse in this area and few testholes are deep enough to reach this depth, so the actual saturated thickness is unknown. However, it is known that the aquifer is thick beneath the Sand Hills. Another area of large saturated thickness occurs in the northwest corner of the study area. This too is an area of sparse data, but it is known to be an area of large saturated thickness.

The area south of Lodgepole Creek generally has small saturated thickness, but an area of greater thickness can be seen in southeast Kimball County and adjacent Cheyenne County. A paleovalley exists in this area, which accounts for the greater saturated thickness. The northern part of the Cheyenne Tableland generally has greater saturated thickness than the southern part. Saturated thickness in northern Kimball and Cheyenne Counties exceeds several hundred feet in areas. Not surprisingly, this is in areas of extensive ground-water irrigation.

Southern Garden County has little saturated thickness on both sides of the North Platte valley. This is due to a bedrock high in the area. Note that Blue Creek cuts right through this bedrock high.

Pumpkin Creek valley generally has little saturated thickness but streaks of greater saturated thickness can be seen in places on the map. This is due to a complex pattern of paleovalleys and fractured Brule Formation in this area. The saturated thickness in this area can change substantially over short distances, so this map only gives a general idea of the complexity of the aquifer in this area.

Saturated thickness is shown as small on the Wildcat Hills in figure 7. This is also an area of sparse data, but the saturated thickness is thought to be small on these uplands

Within the North Platte valley, saturated thickness is quite variable. There tends to be more saturated thickness north of the North Platte River than to the south. In Scotts Bluff County and adjacent areas, there tends to be larger saturated thickness just north of the river with an area of smaller saturated thickness to the north of that where there are hills in the bedrock surface and then another area of greater saturated thickness north of the buried hills. An area of larger saturated thickness parallels the North Platte River but is offset from the river. This is in an area of dense data, so this configuration is thought to be correct.

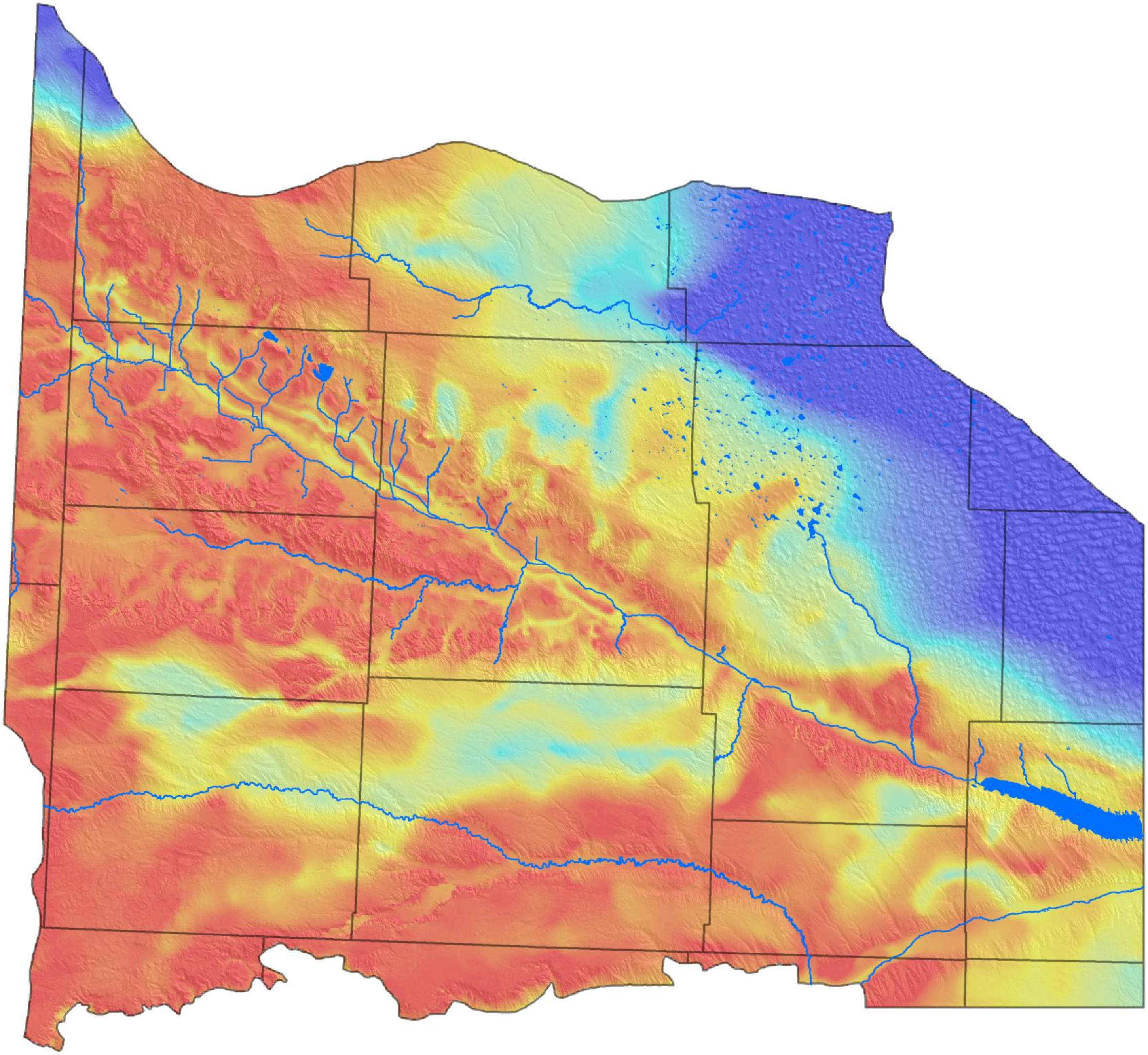


Figure 7. Saturated thickness of the High Plains aquifer. Values range from 0 ft (red) to 870 ft (blue).

Recharge

Prior to settlement, the recharge to the aquifer was due to precipitation on rangeland. After settlement, recharge occurred due to precipitation on croplands. Beginning in the late 1800s, canals were used to irrigate with surface water and this caused various types of recharge. Later, ground water was used to irrigate crops and this caused addition recharge. These various types of recharge are discussed in detail in the Model Inputs section.

Discharge

The primary discharge from the aquifer is to streams and rivers that drain the area. During times between precipitation events, streamflow is maintained by discharge from the aquifer. This steady flow of ground water to the streams is called baseflow.

The discharge to streams prior to development of the surface-water system is based on model simulations described later in this report. There is no gaged data to compare these values to, but the values given here seem reasonable.

The North Platte River and its tributaries are the primary discharge areas for the aquifer. Prior to the development of the surface-water system, most of discharge occurred to the North Platte River and the tributaries had little flow. Upstream from the Bridgeport gage, only Horse Creek, Sheep Creek, Tub Springs Drain, and Red Willow Creek had baseflow greater than one cubic foot per second, and Horse Creek had the largest flow. In contrast, the main stem of the North Platte River gained over 70 ft^3/s above the Bridgeport gage (fig. 3). Between the Bridgeport gage and the Lisco gage, Pumpkin Creek gained 36 ft^3/s and the main stem of the North Platte River gained 58 ft^3/s. Between the Lisco gage and the Lewellen gage, Blue Creek gained 67 ft^3/s and the main stem of the North Platte River gained 68 ft^3/s. After the development of the surface-water system, the tributaries above the Bridgeport gage had considerable baseflow.

Blue Creek, which drains the Sand Hills, was the largest tributary to the North Platte River in terms of baseflow. Blue Creek captures much of the recharge that occurs in the Sand Hills with the remainder going to evapotranspiration within the Sand Hills or the North Platte River.

Snake Creek in the north captures recharge from the northwest part of the study area and from the Alliance Tableland. This stream moves water to the east where Snake Creek disappears into the Sand Hills.

Lodgepole Creek and the main stem of the South Platte River capture discharge from the aquifer in the southern part of the study area. The main stem of the South Platte River captures about three times as much discharge as does Lodgepole Creek. Recharge in the southern part of the model was relatively small, so discharge from this part of the model was also small.

A secondary mechanism of discharge from the aquifer is to evapotranspiration. In some parts of the study area, the water table is at or near land surface and water can be removed from the aquifer directly by evapotranspiration. The largest such evapotranspiration area is in the Sand Hills around the area of numerous lakes in northern Garden County and the part of Sheridan County in the study area. This evapotranspiration area extends up Snake Creek valley and into Morrill County. A smaller evapotranspiration area in the Sand Hills is in Arthur County. Lakes are less numerous in this area. Another smaller evaporation area occurs in the upper part of Pumpkin Creek valley. There are only a few lakes in this area and they dried up after development of ground water.

There are also evapotranspiration areas along the North Platte River and the South Platte River where the riparian forests can use water directly from the aquifer. There also may be evapotranspiration areas along some of the smaller streams, but those are ignored in this study.

Springs also discharge water from the aquifer, but to a much smaller extent than the other mechanisms discussed above. A total of 39 springs were identified in the study area, all near the southern boundary. In total, these springs discharged only a few cubic feet per second.

Beginning with the ground-water development period, pumpage becomes an artificial discharge from the aquifer. Pumpage is discussed in detail in the Model Inputs section.

Conceptual Flow Model

A conceptual flow model is a narrative description of the characteristics of the ground-water flow system that are important to constructing the numerical model. The important characteristics are dependent on the ultimate use of the model. The conceptual model includes the state of the flow system at the beginning of the simulation period, how the flow system interacts with external sources or sinks of water, the lateral and vertical boundaries of the model, and what happens to the elevation or flow of water at these boundaries. For example, part of the conceptual model is how the hydraulic conductivity (parameter describing the ability of the aquifer to transmit water) varies over the model area.

The state of the flow system at the beginning of simulation describes whether the system is in a state of dynamic equilibrium or in a state of long-term change. Recharge from applied irrigation water is an example of an external source of water and evapotranspiration from wetland plants that directly tap the aquifer is an example of an external sink of water. The details of the conceptual model may evolve as the numerical model evolves, but the basic framework generally is understood at the start of model construction.

Ground-Water Flow

Ground-water flow in the study area is generally from west to east and more locally, to streams and rivers that drain the aquifer. Where the potentiometric surface contours (fig. 5) veer upstream along the North Platte River and Lodgepole Creek, ground-water flow is toward the streams. Ground water also flows to other streams in the area, although this is not so obvious in the potentiometric surface.

Ground water both enters and leaves the study area along the western boundary or the study area. Ground water leaves the study area along the eastern boundary where the aquifer continues beyond the study area. Ground water is not thought to enter or leave the study area across the northern or southern boundaries of the study area.

Flow System History

The history of the ground-water flow system in the study area can be broken into three periods. The first period, called the pre-canal period, ended in the late 1800s. Although there are water rights on Lodgepole Creek dating to 1876 and water rights on Cedar Creek dating to 1882, the first large water right from the North Platte River is for Tri-State Canal and is dated 1887. The last large water rights from the North Platte River are for Interstate, Gering-Ft. Laramie, and Northport Canals and are dated 1904. For convenience in this report, the pre-canal period is defined as ending in 1895 because that is when enough canals were operating to substantially alter the ground-water flow system. In the numerical model, all canals were assumed to come online in 1895. The ground-water flow system came into equilibrium with canals within a few years to decades, so assuming all canals came online in 1895 had little effect on the later periods simulated by the numerical model.

The second period, called the pre-ground-water development period, ended in the 1950s. Prior to that time, the technology did not exist to pump ground water from considerable depths. The earliest registered irrigation well in the study area was in Scotts Bluff County and was completed in 1905. Through 1939 there were 165 irrigation wells, mostly in North Platte valley, South Platte valley, and Lodgepole valley. Through 1949 there were 532 irrigation wells, including some in the tablelands of Box Butte County. Through 2010 there were 5999 irrigation wells, including 49 that had no reported completion date. For convenience in this report, the pre-ground-water development period is defined as ending in 1953 because that is when enough wells were operating to substantially alter the ground-water flow system. In the numerical model, wells with a completion date prior to 1953 were assumed to come online in 1953. The year 1953 also was chosen because that is the year of the first aerial photography developed for this project ("Western Water Use Management Model Irrigated and Dryland Acreage Assessment", May 2012).

External Boundaries

The external boundaries of the numerical ground-water flow model include the lateral boundaries of the study area, the lower boundary of the aquifer, and the upper boundary of the aquifer. The lateral boundaries of the aquifer were chosen to be along no-flow boundaries where that was practical. As the name implies, no ground water crosses a no-flow boundary. No-flow boundaries occur on ground-water divides, along ground-water flow lines, and at the lateral extent of the aquifer. The northern and southern boundaries of the study area are generally thought to be no-flow boundaries. The northern boundary follows either ground-water divides or flow lines. The southern boundary follows the lateral limit of the High Plains aquifer, except in the extreme eastern part, where the boundary approximately follows a ground-water flow line.

There is generally flow across the western and eastern boundaries of the study area. Much of the western boundary of the numerical model consists of a line 6 mi west of the Wyoming-Nebraska Stateline. This line is thought to be far enough west that any errors in estimating ground-water flow across this line or estimating ground-water levels along this line would have little effect on the model in Nebraska. The southern part of the western boundary either follows a ground-water divide or a ground-water flow line, except in Lodgepole valley, and thus also is a no-flow boundary. The eastern boundary of the numerical model is a north-south line crossing Kingsley Dam on Lake McConaughy. This boundary is at least 16 mi east of North Platte Natural Resources District and South Platte Natural Resources District, so any errors in estimating flow across this line would have little effect on the model within these districts.

The lower boundary of the High Plains aquifer consists of the unfractured part of the Brule Formation. The Brule Formation is a siltstone that is generally easy to distinguish from overlying units. The Brule Formation tends to be unfractured in much of the study area, with Pumpkin Creek valley, Lodgepole Creek valley including Sidney Draw, and the south side of North Platte River valley being notable exceptions (Cannia and others, 2006, fig. 25). It is difficult to distinguish unfractured Brule

Formation from fractured Brule Formation except in carefully drilled test holes. Even where the upper part of the Brule Formation is fractured and transmits water, the lower part of the unit tends to be unfractured and does not transmit water. Little water is thought to cross the lower boundary of the High Plains aquifer.

By definition, the upper boundary of the aquifer is the water table. Considerable water crosses the upper boundary of the aquifer. This is discussed in the Internal Boundaries and Aquifer Stresses sections of this report.

Internal Boundaries

Internal boundaries of the aquifer are areas in which water can either enter or leave the ground-water flow system. Streams and rivers (hereafter collectively referred to as streams) in connection with the water table are one type of internal boundary. Several lakes in the area, including Lake McConaughy, Lake Minatare, Lake Alice, Winters Creek Lake, and Lake Alice No. 2, are considered internal boundaries of the aquifer. The numerous lakes in the Sand Hills are lumped into another type of internal boundary.

Evapotranspiration areas where water can be directly removed from the aquifer also are internal boundaries. Two types of evapotranspiration areas are described in this report. The riparian evapotranspiration areas generally consist of cottonwood, willow, elm, ash, and Russian olive trees, along with shrubs and smaller plants. These areas are most obvious along the North Platte River and South Platte River, but are found along most streams and elsewhere. Only those areas along the North Platte River and South Platte River are large enough to be included in the numerical model.

Non-riparian evapotranspiration areas generally consist of small wetland plants and open water in direct connection to the water table. The largest non-riparian evapotranspiration areas are in the Sand Hills where there are numerous lakes in connection with the water table. This evapotranspiration area also follows Snake Creek in Box Butte and Sioux Counties. This evapotranspiration area also extends around wetlands and small lakes in northern Morrill County. Several non-riparian evapotranspiration areas occur in upper Pumpkin Creek valley in Banner and Scotts Bluff Counties.

Numerical Model Construction

After developing a conceptual model, a numerical flow can be constructed. The numerical model simulates flow within an aquifer and the exchange of water between the aquifer and the external environment. The numerical ground-water flow model necessarily simplifies and aggregates the true system, but includes those features important to the intended uses of the model. This numerical model was constructed to simulate and investigate the important effects of recharge to and discharge from the regional aquifer. Important regional effects include changes in water levels and changes in ground-water discharge to or ground-water recharge from streams.

The following assumptions were made to construct this numerical flow model:

- Flow in the aquifer obeys Darcy's Law of water movement through porous media, and mass and energy are conserved. These assumptions are valid over the scale at which this model was constructed.
- The density and viscosity of water are constant over space and time. This assumption is approximately true and any small variations in water density or viscosity would be masked by the uncertainties in model inputs.
- Model parameters are uniform within 40-acre areas. This assumption is unlikely but is appropriate because the model is intended as a regional representation of the ground-water flow system and because the spacing of test holes and other data points to define model inputs is large compared to 40-acre areas.
- The interchange of water between the aquifer and streams and lakes can be adequately simulated as one-dimensional flow through a discrete streambed or lakebed layer. Such a discrete layer may or may not actually exist, but this conceptualization is appropriate over the scale at which this model was constructed.
- Ground-water flow throughout the model is two-dimensional. This assumption is a consequence of treating the aquifer as a single layer. However, vertical-flow components are small compared to horizontal-flow components over much of this model area, so this assumption is appropriate over the scale at which this model is constructed.
- Hydraulic conductivity is isotropic within a 40-acre model cell in the horizontal direction. Because the aquifer is predominately composed of fluvial and eolian deposits, some small-scale anisotropy probably exists, but changes direction over small areas. The assumption about isotropy within a model cell in the horizontal directions is valid at the scale of this model. Large-scale anisotropy is represented in the model as areal variation in hydraulic conductivity from cell to cell.

MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996; and Harbaugh and others, 2000) was selected as the ground-water flow modeling code for this study. MODFLOW is a widely used flow simulation code that uses block-centered finite-difference techniques to solve the three-dimensional partial differential equations that describe the flow of ground water through porous media. The finite difference techniques treat space and time as finite sets of discrete points rather than as continuums. This approach introduces a negligible error into the solution, compared to the uncertainties associated with the real system. The version of MODFLOW used in this study was MODFLOW-2000.

To use the block-centered finite-difference technique, the study area was subdivided into a grid with individual blocks called cells. Although MODFLOW allows variation in cell sizes within the grid, a constant cell size was used in this study. Aquifer properties are assumed to be uniform within a single cell, but can vary between cells. Water levels are calculated at the centroid, or node, of each active cell. MODFLOW accounts for the flow of water between adjacent cells and the flow of water into and out of each individual cell from external boundaries, internal boundaries, and aquifer stresses. MODFLOW generates a finite-difference equation for each active cell in the model and uses numerical techniques to simultaneously solve these equations. Numerical techniques make successive approximations, called iterations, to obtain the solution. When the difference between successive approximations becomes negligible, a solution is said to have been reached.

The MODFLOW-2000 Global Process requires four files. The *name file* signals what packages are to be used and contains the file names and FORTRAN units from which inputs will be read or outputs will be written. The *discretization file* describes the areal and temporal discretization and contains the tops and bottoms of the model layers. The *multiplier file* and the *zone file* are used if MODFLOW Parameters are used for model inputs. This model does not use MODFLOW Parameters.

MODFLOW-2000, version 1.19.01 dated 03/25/2010 was used in this study. The following MODFLOW packages were used, followed by a brief explanation of what is done in the package:

- The Basic Package, version 6 dated 01/11/2000, was used to define the active cells in the model and initial water levels for the simulation. It was also used to control output from the model.
- The Layer-Property Flow Package, version unknown, was used to define the hydraulic properties of the aquifer and how certain calculations on these properties were made.
- The Strongly Implicit Procedure (SIP) Solver Package, version 5 dated 09/01/1993, was used to define parameters to simultaneously solve the equations that MODFLOW created and to determine when a solution was achieved.

- The Recharge Package, version 6 dated 01/11/2000, was used to define recharge over time over the study area.
- The Well Package, version 6 dated 01/11/2010, was used to define pumpage over time over the study area.
- The Evapotranspiration Package, version 6 dated 12/14/2000, was used to define evapotranspiration parameters.
- The Stream Package, version 6 dated 06/1998, was used to define which cells were stream cells, the order of the stream cells, and the properties of the streams.
- The General-Head Boundary Package, version 6 dated 01/11/2000, was used to define which cells were lake cells and the properties of the lakes.
- The Drain Package, version 6 dated 01/11/2000, was used to define where cells were spring cells and the properties of the springs.

As instructed by the various packages, MODFLOW produced two output text files, the *global file* and the *list file*. These contain general information about the simulation. The *list file* contains a water budget for selected time steps in the simulation. The water budgets can be checked to see how well they close, indicating how accurate the solution is.

MODFLOW also produced three output binary files. The *head file* contains simulated water levels for each cell in the study area for each time step where output was requested. The *drawdown file* contains the simulated change in water levels for each cell in the study area since the simulation began for each time step where output was requested. The *cell-by-cell flow file* contains water budget information for each cell in the study area for each time step where output was requested. This includes streamflow into or out of each stream cell, lake flow into or out of each general head boundary cell, flow into or out of each constant head cell, and flow out of each drain cell. It also includes recharge, pumpage, and evapotranspiration for each cell.

Ground water Vistas (Version 6.30), developed by Jim and Doug Rumbaugh, was selected as the pre- and post-processor for MODFLOW. Vistas supports a number of ground-water flow and transport codes in addition to MODFLOW. Vistas supports a wide variety of data inputs and outputs, including Geographic Information System (GIS) shapefiles and various types of text files. Model inputs can be created within Vistas or imported from external sources. In this study, most data inputs were created externally, with small changes being made within Vistas. Vistas uses model inputs to prepare the files required by MODFLOW. The output from MODFLOW can be read by Vistas, and Vistas displays the results using maps, graphs, cross sections, and tables. These capabilities allow Vistas users to efficiently conceptualize and simulate flow in the ground-water system. Vistas allows the conceptual and numerical models to evolve as the simulations are compared to historic hydrologic data.

Spatial Discretization

The grid for the numerical model consisted of 476 rows and 520 columns for a total of 247,520 cells. There were 177,780 active cells and 69,740 inactive cells. The grid lines defining the edges of cells were oriented in a north-south, east-west fashion with a spacing of 1320 ft. Each cell covered 40 acres. The model was constructed using Nebraska state plane coordinates with North American Datum of 1983. The southwest corner of the grid was at X=495,000 and Y=377,520. The grid was coincident with, although finer, than a grid that Nebraska Department of Natural Resources requested that all model in the state of Nebraska conform to. A small portion of the grid near the town of Mitchell is shown on figure 8.

Temporal Discretization

The numerical model simulated three distinct periods, the pre-canal period, the pre-ground-water development period, and the ground-water development period. The pre-canal period model simulated the period prior to canals when the hydrologic system was in a state of dynamic equilibrium in which discharge from the aquifer was in equilibrium with recharge to the aquifer and there was no long term change in storage within the aquifer. This state of dynamic equilibrium is called steady state. MODFLOW has the ability to simulate steady state conditions directly, but the flow system in the study area is complex with large changes in saturated thickness in short distances and that makes it numerically difficult to directly simulate steady state conditions.

To achieve steady state, the model instead simulated a 2000-year period, which was more than sufficient time for the system to come into dynamic equilibrium. This 2000-year period was simulated with two stress periods. The first stress period was 400 years long and was simulated with 29,220 time steps of 5 days each. These small time steps allowed to model to evolve slowly and prevented numerical oscillations from incorrectly drying up model cells. The second stress period was 1600 years long and was simulated with 58,440 time steps of 10 days each. These larger time steps allowed the model to run more quickly. For this period, a year was considered to be 365.25 days. The pre-canal period simulation ended May 1, 1895.

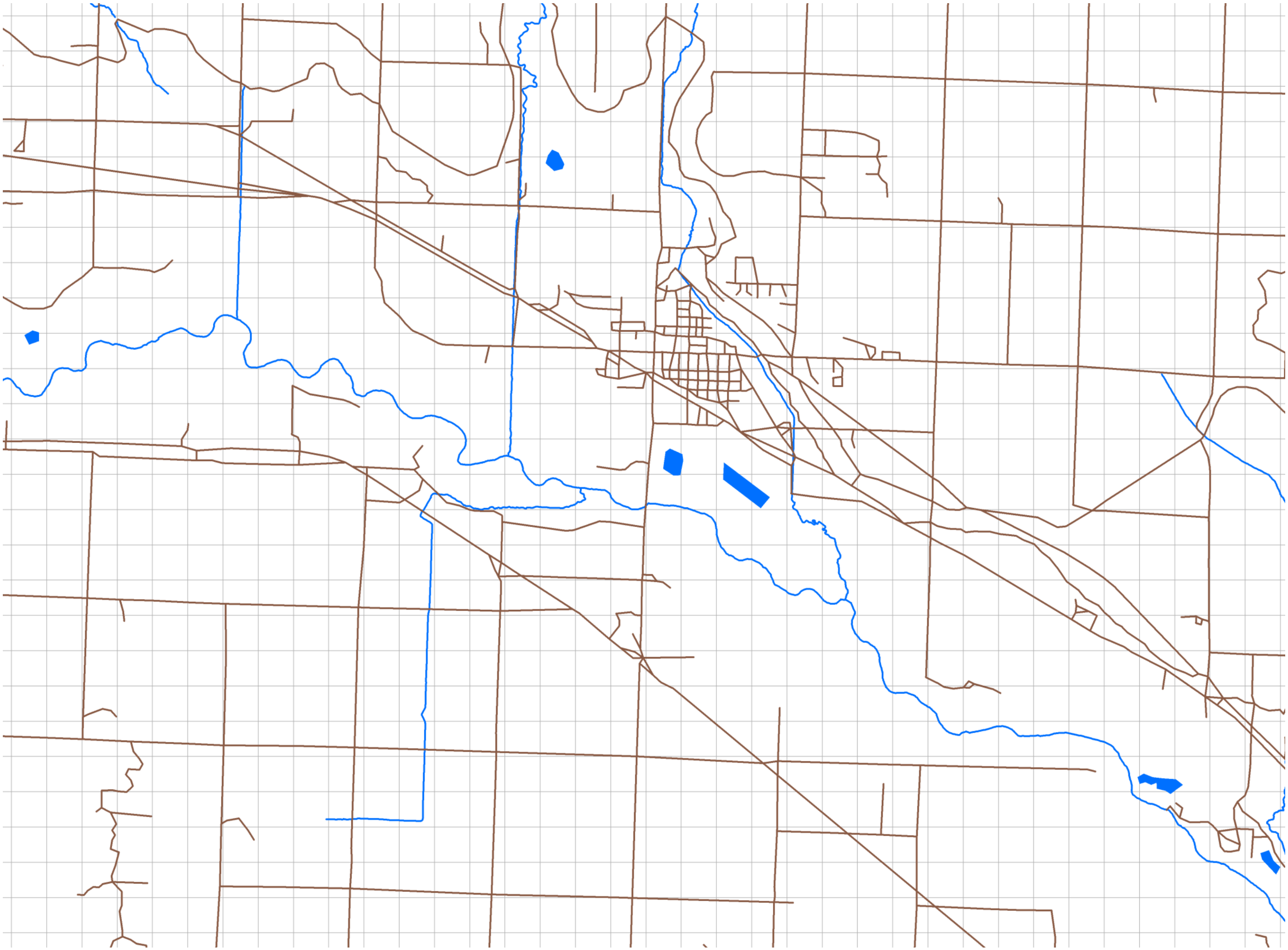


Figure 8. Model grid (gray squares) in the vicinity of Mitchell, Nebraska. Roads are shown in brown.

The pre-ground-water development period was simulated with two stress periods per year. The first stress period was the irrigation season of May through September and was 153 days long. This period was simulated using 30 time steps of 5.1 days each. The second stress period was the non-irrigation season of October through April and was 212 or 213 days long, depending on whether it was a normal year or a leap year. This period was simulated using 42 time steps of approximately 5.0 days each. The pre-ground-water development period simulation ended May 1, 1953.

The ground-water development period was simulated using monthly stress periods ranging from 28 to 31 days long. Each stress period was simulated using six time steps of approximately 5 days each. The ground-water development period simulation ended May 1, 2011.

Model Inputs

MODFLOW requires a number of inputs to simulate the flow system. This includes information on spatial and temporal discretization as described above. This also includes information on external boundaries of the study area, internal boundaries within the study area, initial conditions at the start of the simulation, aquifer properties, and aquifer stress. This additional information on model inputs is discussed in this section.

External Boundaries

MODFLOW requires information at the external boundaries of the study area. These boundaries include the lateral extent of the study area and the base of the aquifer. MODFLOW computes the position of the water table, which in the study area represents the top of the aquifer. MODFLOW also requires information about land surface because MODFLOW changes some calculations if the simulated water table rises above land surface.

Lateral Boundaries

The lateral boundaries of the study area are shown in figure 1. As was discussed in the Conceptual Flow Model section, parts of the lateral boundary of the study area were chosen because no ground water flowed across these parts of the boundary. These parts of the boundary were placed either along a ground-water divide or along a ground-water flow line. These no-flow boundaries were simulated implicitly in MODFLOW by making cells beyond these boundaries inactive.

Ground water flowed across the remainder of the lateral boundaries of the study area. These boundaries were simulated as constant head boundaries in the model and these heads were determined from the map shown in figure 5. At constant head cells, the water level in the cell is set at the beginning of the simulation and is not allowed to change during the simulation. Water flows into or out of the constant head cells to simulated flow across the boundary. There were 467 constant head cells in the model.

Base of Aquifer

The base of aquifer is the lower limit of the aquifer. The base of the High Plains aquifer over most of the study area is unfractured Brule Formation siltstone. Unfractured Brule Formation transmits almost no water so the base of aquifer is considerable impermeable. If the Brule Formation is fractured or contains channel deposits, it can transmit water and is included as part of the High Plains aquifer. In that case, the base of aquifer is the base of the fractures or the base of the channel deposits.

In North Platte River valley and Horse Creek valley in Wyoming, parts of the base of aquifer are mapped as Lance Formation. This is a sandstone, which may exchange small quantities of water with the aquifer. However, even in these cases, the base of aquifer is considered impermeable in this model.

The base of aquifer was mapped by Cannia and others (2006) and was modified by Kuntz (T.A. Kuntz, personal commun., 2011) and that map was used in this version of the ground-water flow model, except as modified in paleovalleys, as described in the Model Construction section. The 100-ft contours from that map were interpolated to the model grid using a procedure in the geographic information system ArcInfo (® ESRI Inc.) called TopoGrid 7x. TopoGrid is a sophisticated procedure to grid elevation and stream line data and TopoGrid has various options and parameters that control the interpolation of the data. Thad Kuntz (Adaptive Resources, Inc.) developed a set of options and parameters that accurately interpolated the base of aquifer to the model grid. The base of aquifer is shown in figure 9.

The base of aquifer at every active model cell was checked against the land surface. The base was above land surface at approximately 350 cells, mostly along escarpments and along the edges of North Platte River valley and Horse Creek valley in Wyoming. Along escarpments, both the base of aquifer and land surface change rapidly over short distances and the base of aquifer is frequently near land surface. The base of aquifer was mapped 6 mi into Wyoming but test holes to control mapping base of aquifer were lacking in Wyoming. Where the base of aquifer was above land surface and where the base was less than 6 ft below land surface, the base of aquifer was set to 6 ft below land surface. This affected approximately 700 model cells. The value 6 ft was selected because evapotranspiration from the shallow water table was allowed to remove water from a depth of up to 5 ft. By using a value larger than 5 ft, evapotranspiration alone could not dry up a model cell.

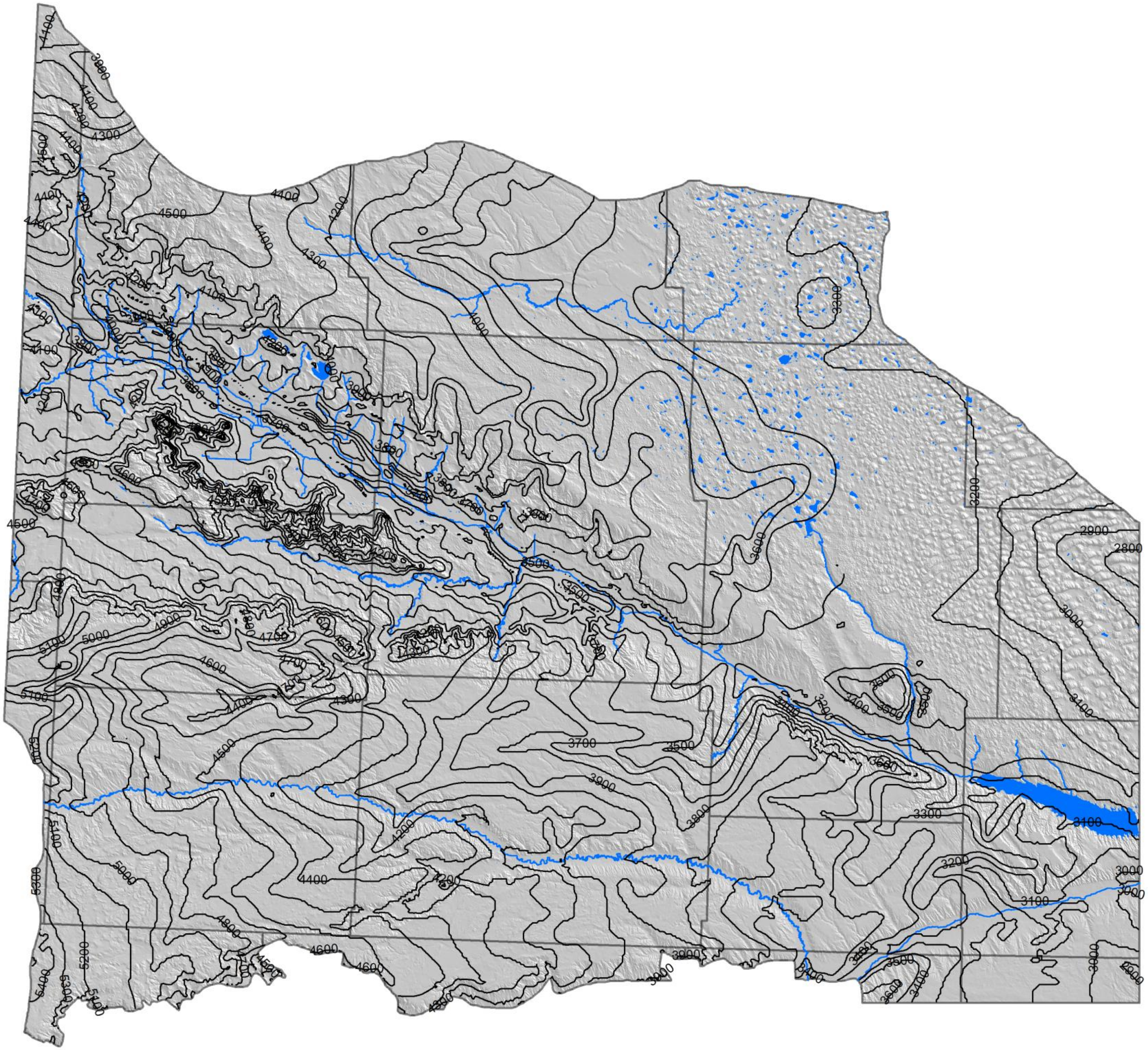


Figure 9. Base of aquifer. Contour interval is 100 ft. Datum is sea level.

Land Surface

A Digital Elevation Model (DEM) of land surface elevation was downloaded from the U.S. Geological Survey (2011). This was a 30-meter DEM with a data point approximately every 100 ft. These data were based on the 1:24,000 series topographic maps. These data points were used to compute an average land surface elevation for each model cell.

MODFLOW-2000 treats land surface as the top of the aquifer if the simulated water level rises above land surface, and as a result, converts the aquifer from unconfined to confined in this case. This is not realistic for the High Plains aquifer in the study area and caused problems with the model. For example, in wetlands and lakes in the Sand Hills, the water table may be at or above land surface and the aquifer remains unconfined. To prevent the aquifer from becoming confined in the model in such a situation, the land surface in the model was set to 100 ft above the actual land surface.

Internal Boundaries

MODFLOW requires information at the internal boundaries of the study area. These boundaries include streams, lakes, and areas where evapotranspiration can remove water directly from the aquifer. Streams in hydraulic connection with the water table can take or contribute water directly from the aquifer, depending on the relative difference between water levels in the aquifer and in the streams and the streambed properties. Lakes in hydraulic connection with the aquifer act in a similar manner as streams in the model. Springs discharge water directly from the aquifer. The discharge depends on the relative difference between water levels in the aquifer and in the springs and the conductance properties of the spring. Evapotranspiration from the aquifer is a function of the water level in the aquifer and this is an internal boundary.

Streams

Rivers, streams, creeks, and drains were simulated in the model as streams, and in reality they all act as streams no matter what they are called. The largest streams in the model in terms of flow are the North Platte River and the South Platte River. Other large streams in terms of length are Lodgepole Creek, Pumpkin Creek, and Blue Creek. Examples of small streams included in the model are Clear Creek, Indian Creek, Silvernail Drain, and Coldwater Creek. The streams included in the model are shown in figure 1.

All larger streams in the study area that flow because they receive ground water from the aquifer were included in the model. Which smaller streams were included in the model was somewhat subjective.

Streams whose perennial length was more than a few miles and whose sustained flow was more than a few cubic feet per second were included. If the Nebraska Department of Natural Resources gaged a stream or estimated streamflow as part of water rights administration, the stream was included in the ground-water flow model. All streams considered for the model were visited by one or more project staff before the decision was made to include or exclude the stream in the model.

Model cells were selected to represent the streams in the model. The model includes 2959 stream cells. The stream cells selected represent the general courses of the streams but do not represent the exact course of the streams. For example, if a stream went through only a corner of a cell, that cell was not likely to be selected as a stream cell. Figure 10 shows stream cells along Kiowa Creek and Horse Creek near the village of Lyman to illustrate the relationship between streams and stream cells. Horse Creek is the east-west feature in the upper part of the figure and Kiowa Creek is the north-south feature near the center. Owl Creek enters Kiowa Creek from the southeast. Stream cells were selected to only represent the perennial parts of the streams that receive ground water. Once streams in the study area become perennial, the downstream sections tend to remain perennial. The exceptions are small streams as they flow over high-permeability sediments at the edge of North Platte valley or Pumpkin Creek valley.

Stream cells have to be numbered in a very specific way to work in MODFLOW. Stream cells are grouped into segments, which represent one or more cells along a stream between tributaries. Within a segment, stream cells are numbered by reach in a downstream order. Both segment numbers and reach numbers must start with one and must be done in a consecutive manner without any gaps in the numbering system. This numbering was done by hand when creating the stream input data.

Stream segments 1 through 41 represented the North Platte. Stream segment 42 represented the isolated part of Horse Creek in Wyoming near the eastern boundary of the study area and segments 43 through 145 represented tributaries to the North Platte River in a downstream direction. The South Platte River was represented by segments 146 through 153 and Lodgepole Creek was represented by segments 154 through 176. Akers Draw, tributary to the North Platte River, was added to the model later and was assigned segment 177. Snake Creek was also added to the model later and was assigned segments 178 through 194.

MODFLOW also needed to know which streams were tributary to other streams. This stream linkage was based on segment numbers and was also done by hand. For example, segment 1 was tributary to segment 2 and segment 2 was tributary to segment 3. Segment 3 and segment 46 (lower most segment of Horse Creek) were tributary to segment 4.

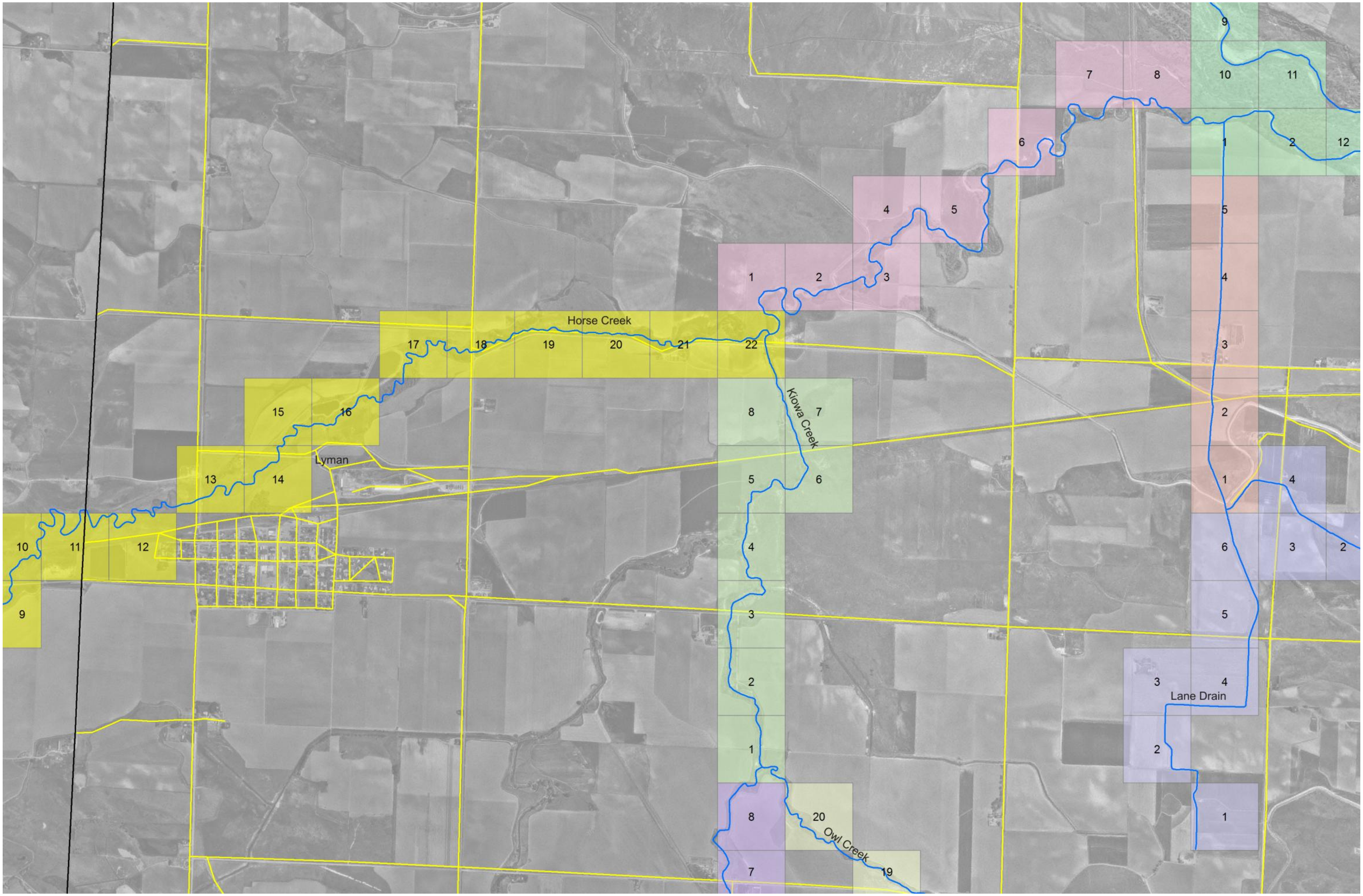


Figure 10. Example of stream cells used in the model in the vicinity of Lyman, Nebraska. Colors represent stream segments and numbers represent stream reaches.

Stream surface elevation is an important model input because the difference between the stream elevation and the simulated water-table elevation below the stream drives simulated flow into or out of the stream. To provide stream surface elevation data, North Platte Natural Resources District and South Platte Natural Resources District hired Nation Engineering Services of Ft. Morgan, Colorado, to determine stream surface elevations at approximately 93 points in the study area. These elevations were accurate to 0.001 ft, more than sufficient for use in the model. These points were where roads provided easy access to the streams. These points are called high resolution points in this section.

Not all streams had high resolution points on them. Some streams had only one or two high resolution points on them. The North Platte River had a high resolution point at every bridge crossing.

The high resolution points were supplemented by elevations determined from 1:24,000 topographic maps near where streams entered or left the study area and near the start of perennial flow on the streams. These points are called supplemental points in this section. Initially, topographic elevations were used between high resolution points, but it was later found that these elevations degraded rather than enhanced the interpolation process and these elevations were then discarded. Streams without high resolution points contained only supplemental points.

Arcs that defined the courses of the streams were downloaded from the National Hydrography Data sets (U.S. Geological Survey, 2010) that were based on 1:24,000 topographic maps. These arcs were used in the interpolation process to estimate stream surface elevation between high resolution points or supplemental points. These arcs were first joined into a single arc for each stream and the arcs were then split at high resolution points or supplemental points. The arcs were densified so that they contained a vertex at least every 100 ft along the course of the stream.

Stream surface elevations along the North Platte River, South Platte River, Lodgepole Creek, and the isolated part of Horse Creek in Wyoming were interpolated between high resolution points or supplemental points based on the cumulative length of the arc between the upstream end of the arc and every vertex on the arc, which accounted for the sinuosity of the stream. The arcs representing the North Platte River had a vertex at the mouth of each tributary stream, so this interpolation process resulted in an interpolated stream elevation at the mouth of each first-order tributary (stream directly tributary to the North Platte River). Stream surface elevations along first-order tributaries were then interpolated between high precision points, supplemental points, and mouths of the tributaries. For example, Horse Creek is a first-order tributary of the North Platte River, so stream surface elevations were interpolated at vertices along Horse Creek. This interpolation resulted in an elevation at the mouth of each second-order tributary. For example, Kiowa Creek is tributary to Horse Creek and the interpolation process along Horse Creek resulted in an interpolated elevation at the mouth of Kiowa Creek. Stream surface elevations along second-order tributaries were then interpolated between high precision points, supplemental points, and mouths of these tributaries. The process was then repeated for third-order tributaries (tributaries to second-order tributaries). For example, Owl Creek is a third-order tributary because it is tributary to Kiowa Creek, which in turn is tributary to Horse Creek. The process ended here because no fourth-order tributaries were included in the model.

Stream surface elevations were used to calculate two other model inputs required by MODFLOW. These include elevation of top of streambed and elevation of bottom of streambed. Elevation of top of streambed was calculated by assuming a constant depth of water in the stream. A depth of 5 ft was assumed for the North Platte River and a depth of 3 ft was assumed for the South Platte River. A depth of 2 ft was assumed for all other streams. Elevation of top of streambed was calculated as stream surface elevation minus assumed depth. Elevation of bottom of streambed was calculated as top of streambed elevation minus 5 ft. The elevation of bottom of streambed controls when leakage out of a stream reaches a limiting value. Once the simulated water level in the aquifer declines below the bottom of the streambed, a unit downward gradient is achieved and further declines in the simulated water level do not increase stream leakage. Such a situation is unlikely to occur in the study area.

MODFLOW simulated the interaction between the aquifer and the stream as one-dimensional flow through a hypothetical low-permeability streambed. A lumped parameter, termed conductance, accounted for hydraulic conductivity and thickness of a low-permeability streambed as well as the width and length of the streambed in each model cell. In many instances, no identifiable low-permeability streambed exists (McDonald and Harbaugh, 1988, p. 6-1). This is particularly true in this study area. Although streambed conductance was refined during model calibration, stream length, stream width, and streambed thickness were estimated for every stream cell for possible future use in refining streambed conductance. Stream width was estimated using 2009 aerial photography. Stream length was estimated as the length of the stream arc in each stream cell. Streambed thickness was set to a constant 5 ft.

Stream width may also be used by MODFLOW if it calculates stream stage. To calculate stream stage, MODFLOW also needs the slope of the stream and Manning's roughness coefficient. Stream slope was calculated using the high resolution points or supplemental points and the length of the stream arc between the points. Manning's roughness coefficient was set to a uniform 0.03, a typical value for clean and straight natural streams (Prudic, 1989, table 1). Although MODFLOW was not allowed to calculate stream stage in this study, these parameters were defined for possible future refinement of the model.

MODFLOW also needs to know the streamflow at the start of the streams. This only applies to North Platte River, South Platte River, Horse Creek, and Lodgepole Creek because all other streams originate in the study area. The estimated flow of North Platte River at the western model boundary was 300 ft^3/s and the estimated flow of South Platte River at the southern model boundary was 54 ft^3/s for May-September and was 218 ft^3/s for October-April. The estimated flow of Horse Creek, at both the isolated segment and at the main segment, was 12 ft^3/s. The estimated flow of Lodgepole Creek at the western model boundary was 2 ft^3/s. All of these values were based on the estimated baseflow of these streams.

Lakes

Lakes in connection with the water table, except for Sand Hill lakes, were handled in the model as general head boundaries. Lakes simulated in the model include Lake McConaughy, Lake Minatare, Lake Alice, Winters Creek Lake, and Lake Alice No. 2 (or Little Lake Alice). Lake Minatare, Lake Alice, Winters Creek Lake, and Lake Alice No. 2, collectively called the Inland Lakes, were added to the model in 1915. Lake McConaughy was added to the model in 1941. There were 592 general head boundary cells in the model.

MODFLOW simulated the interaction between the ground-water system and lakes as one-dimensional flow through a hypothetical low-permeability lakebed. A lumped parameter, termed conductance, accounted for hydraulic conductivity and thickness of the low-permeability lakebed as well as the area of the lakebed in each model cell.

The conductance for the lakes was set to 1.74E+06 ft^2/d, which is the same as the conductance for Lake McConaughy in the previous model (Luckey and Cannia, 2006, p. 38).

The calculation of flow between a lake cell and the aquifer is similar to the calculation of flow between a stream cell and the aquifer. However, there is no upper limit on the rate at which a lake can lose water to the aquifer such as when steam loss to the aquifer is limited when a unit downward gradient is reached.

Lake surface elevation is an important model input because the difference in lake elevation and the simulated water-table elevation below the lake drives flow into or out of the lake. Lake surface elevation for Lake McConaughy was provided by Cory Steinke (The Central Nebraska Public Power and Irrigation District, electronic commun. October 18, 2011). This elevation data was available for the life of the reservoir. Lake surface elevation data for Lake Alice, Lake Alice No. 2, Lake Minatare, and Winters Creek Lake were provided by U.S. Bureau of Reclamation (2012). These elevation data were available for 1990-2010. For other dates, average lake surface elevation was used.

Springs

Springs discharging from the aquifer were simulated as drains in the model. Water may be discharged from the aquifer to a drain, but water may not enter the aquifer from a drain. This is what happens at a spring. A drain may be thought of as a stream with a one-way valve on it. The calculation of flow between a drain cell and the aquifer is similar to the calculation of the flow between a stream cell and the aquifer. The conductance for the springs was set to an arbitrary uniform 5000 ft^2/d. There were 39 drain cells in the model.

Evapotranspiration Areas

Evapotranspiration areas occur in the model where water can be directly removed from the aquifer. The evapotranspiration areas are shown in figure 11. In MODFLOW, the evapotranspiration rate was a function of the simulated water level in the aquifer, so these areas are internal boundaries of the model.

MODFLOW requires the maximum evapotranspiration rate, the ground-water elevation at which this maximum rate occurs (herein called the evapotranspiration surface), and an extinction depth. If the simulated water level in the cell is at or above the evapotranspiration surface, evapotranspiration occurs at the maximum rate. If the simulated water level is deeper than the extinction depth below the evapotranspiration surface, zero evapotranspiration occurs. If the simulated water level is between the evapotranspiration surface and the extinction depth below this surface, evapotranspiration rate is a linear interpolation between the maximum rate and zero.

In the Sand Hills lakes area, evapotranspiration probably occurs in the inter-dune areas of wetlands and lakes and probably does not occur on the upper parts of the dunes. To account for this, the evapotranspiration surface was set to the mean land surface elevation over the model cell. Along the North Platte River and South Platte River, there probably is little difference between average land surface and minimum land surface, so mean land surface also was used there.

The maximum evapotranspiration rate was estimated as the difference between lake evaporation and precipitation times a factor. The factor was 0.5 and was based on woodland evapotranspiration studies near Gothenburg and Odessa, Nebraska (M.K. Landon, U.S. Geological Survey, oral communication, July 2004). The maximum evapotranspiration rate ranged from 16.0 in/yr in the west to 14.5 in/yr in the east and varied is roughly linear fashion.

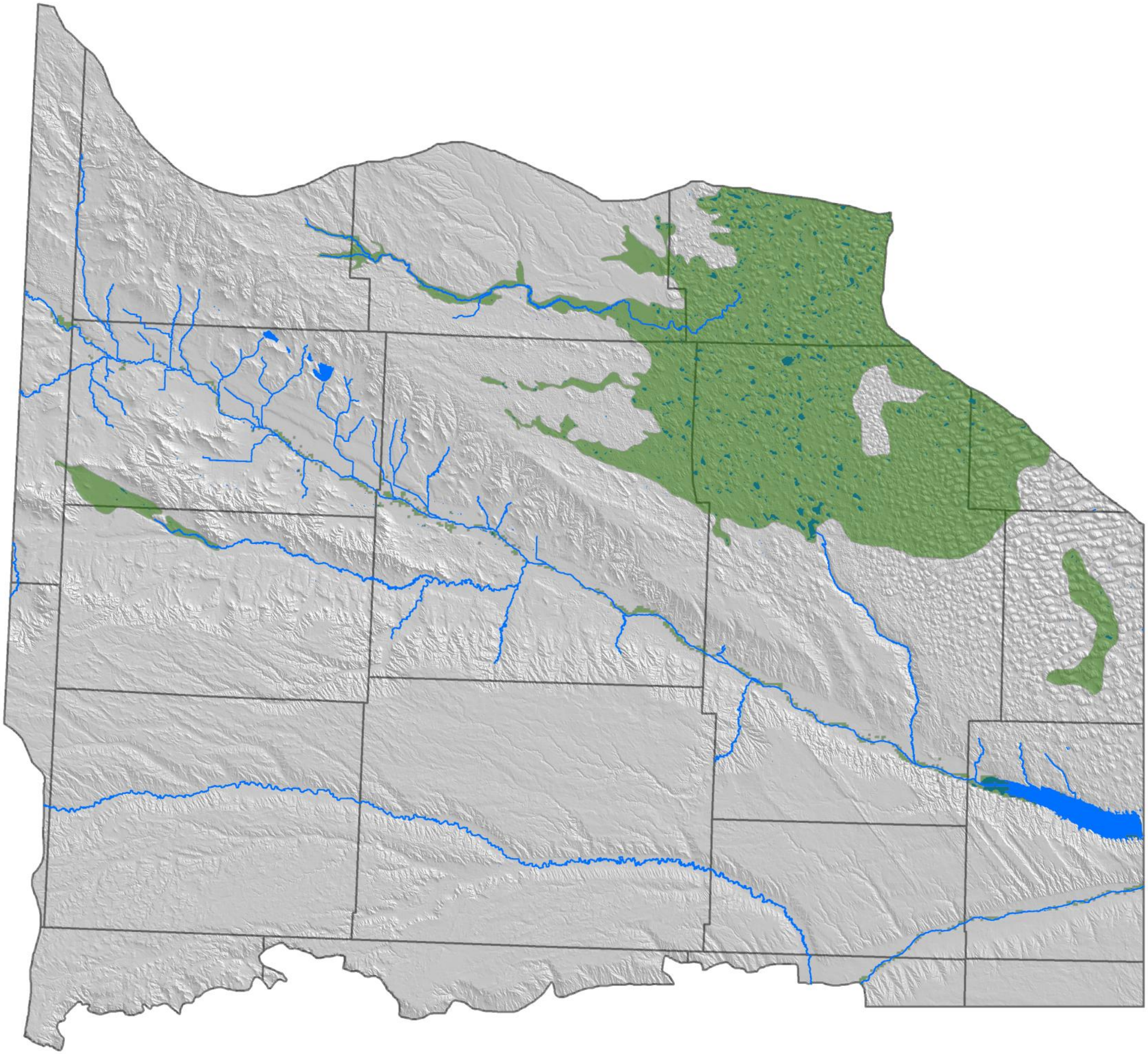


Figure 11. Evapotranspiration areas used in the model. Maximum evapotranspiration rates range from 14.5 in/yr to 16.0 in/yr from east to west.

The evapotranspiration areas along the North Platte River and South Platte River included cells that consist of at least 50 percent riparian forest or wetlands (Dappen and others, 2006) but excluded cells that were used to simulate the streams. The exclusion prevented cells from representing multiple boundary conditions

Initial Conditions

MODFLOW needs to know the initial water levels at the beginning of the simulation. As the simulation progresses, the simulated water levels from the previous time step become the initial water levels for the next time step. Likewise, the final water levels for the pre-canal period become the initial water levels for the pre-ground-water development period and the final water levels for the pre-ground-water development period become the initial water levels for the ground-water development period.

The pre-canal period simulation was a steady state simulation, although steady state was achieved using a 2000 year transient simulation. One characteristic of a steady state simulation is that the final water levels are independent of the initial water levels, so long as steady state has been achieved. As a result, the initial water levels for the pre-canal period simulation are immaterial.

For the pre-canal period simulation, the initial water levels were set at 0.01 ft above the base of aquifer. This was done because MODFLOW tends to oscillate until a correct solution is reached for a time step, so simulated water levels may be too low or too high as MODFLOW iterates to a solution. The oscillations dampen as MODFLOW gets closer to a solution, but the early iterations can be problematic. The small initial saturated thickness prevents MODFLOW from estimating a solution for a cell during an iteration that is below the base of aquifer. If this were to happen, the cell would be marked as dry and the cell would no longer be an active cell. The 0.01 ft initial saturated thickness was selected after some initial tests indicated that it prevented dry cells and allowed the simulated water level in the aquifer to rise slowly over time during the pre-canal period simulation.

Aquifer Properties

There are two aquifer properties that are meaningful to the model. Hydraulic conductivity is a measure of how easily water flows through the aquifer. Specific yield is a measure of how much aquifer space is needed to store water. MODFLOW requires a third aquifer property, specific storage, but this property is only used if the aquifer becomes confined. The High Plains aquifer in the study area is unconfined and great care was exercised in the model to prevent it from becoming confined. Specific storage was set to 1.0E-04 everywhere in the model because MODFLOW required some value, even if it is not used.

Hydraulic Conductivity

Hydraulic conductivity is the aquifer parameter that describes the rate of ground-water flow through a unit thickness of aquifer (1 foot) and a unit width of aquifer. In this report, hydraulic conductivity is the amount of water, in cubic feet, that moves through a square foot of the aquifer measured at a right angle to the direction of flow, under a gradient of one foot per foot, in one day. The measurement is taken at the existing viscosity of the water. Hydraulic conductivity is primarily a function of the aquifer characteristics, but is also a function of water temperature because temperature affects viscosity. The units of hydraulic conductivity are feet per day (ft/d). In spite of the units, hydraulic conductivity is not the velocity of water in the aquifer. The velocity of water in the High Plains aquifer is much smaller because the gradient in the aquifer is typically much less than one foot per foot.

The hydraulic conductivity distribution used in this model is shown on figure 12. Hydraulic conductivity was based on the lithology of test holes, specific capacity tests in wells, saturated thickness, and the existence of paleovalleys in the base of aquifer. Hydraulic conductivity was largest along the valleys where the aquifer is made up of alluvium. Hydraulic conductivity was smallest along escarpments where the aquifer is made up of colluvium. Hydraulic conductivity also was small on the bluffs on the south side of North Platte valley in the eastern part of the model. Hydraulic conductivity also was small in much of the northwestern part of the model. Elsewhere, hydraulic conductivity generally ranged from 10 ft/d to 40 ft/d.

Hydraulic conductivity in the paleovalleys in the base of aquifer was 120 ft/d, except where the paleovalleys underlay alluvium. These higher values represented coarser sediments in the paleovalleys laid down by higher velocity streams that cut the paleovalleys.

Specific Yield

Specific yield is the aquifer parameter that describes the amount of water released from the entire thickness of an unconfined aquifer due to a unit decline in the water table (1 foot). Specific yield is a dimensionless number. Specific yield is primarily a function of the aquifer properties at the water table because that is where most of the water is released as the water table declines. Specific yield is smaller than the porosity of the aquifer at the water table because not all of the water in the pore space is released as the water table declines. Some water is held by the aquifer grains under capillary forces and this portion of the water is called specific retention.

The specific yield distribution used in this model is shown in figure 13. The specific yield distribution was similar to the previous model (Luckey and Cannia, 2006, fig. 13), although the values were changed.

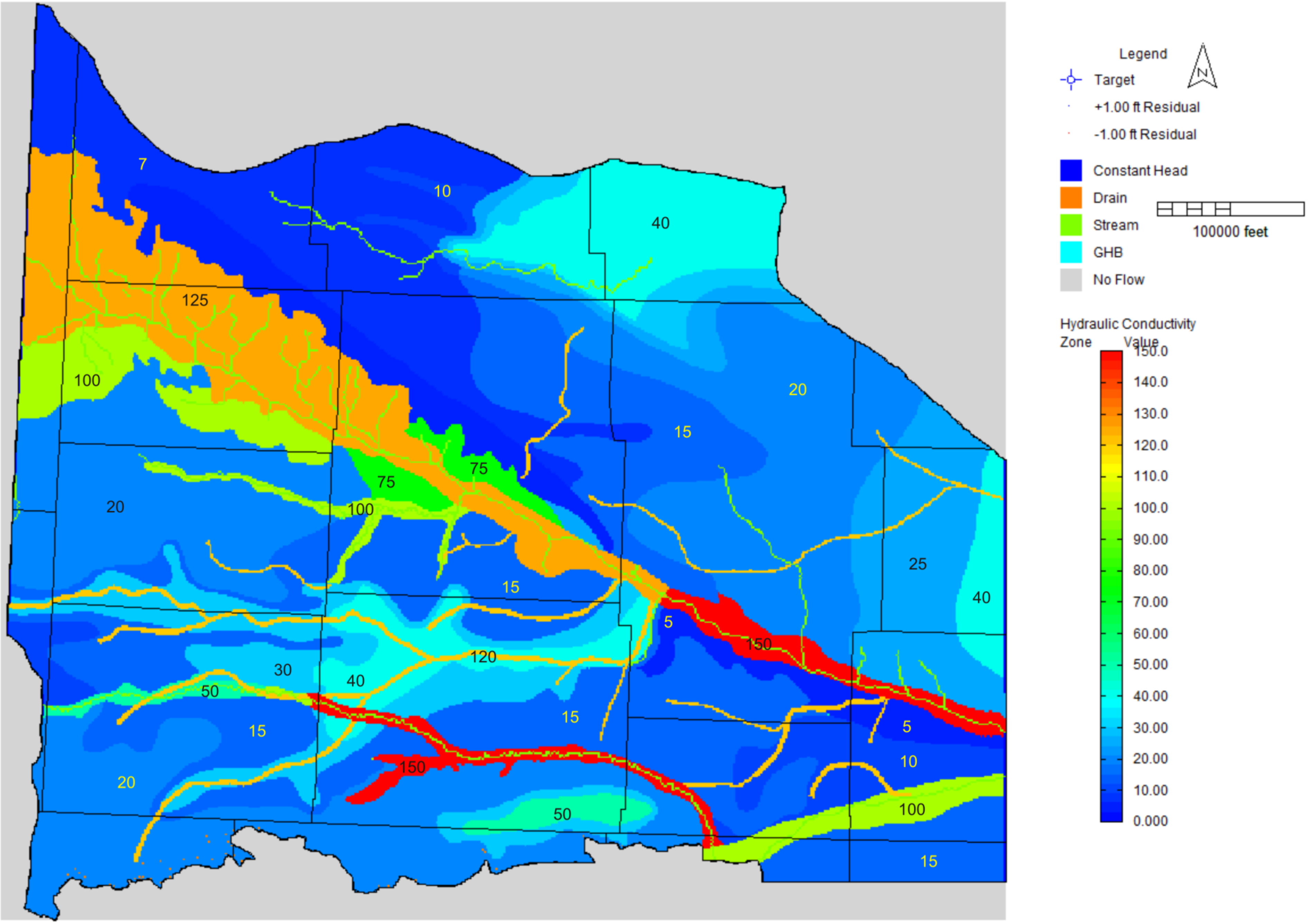


Figure 12. Hydraulic conductivity used in the calibrated model. Units are feet per day.

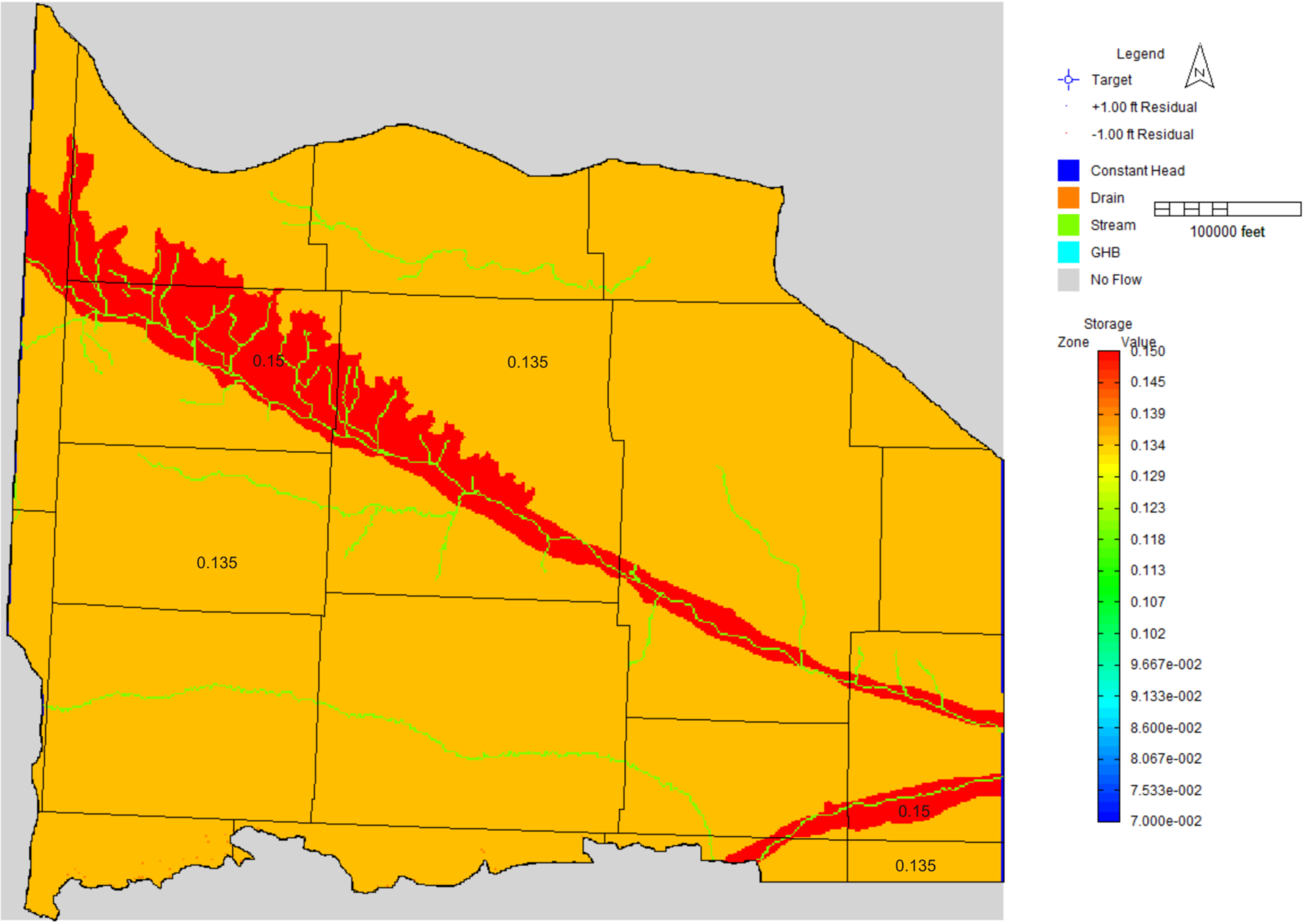


Figure 13. Specific yield used in the calibrated model. Units are dimensionless.

The specific yield was assigned a value of 0.15 where the aquifer consisted primarily of alluvium and a value of 0.135 elsewhere. During calibration, specific yield was reduced uniformly by 25 percent from the previous values and the lower values for the Arikaree Group were eliminated to get the above values to better simulate the fall-to-spring change in streamflow.

Aquifer Stresses

Aquifer stresses either add water to the aquifer or remove water from the aquifer. Aquifer stresses exclude evapotranspiration in this report. Aquifer stresses are generally more areally extensive than internal boundaries. In addition, the amount of water added or removed via aquifer stresses is independent of the water level in the aquifer.

Two aquifer stresses are considered in this report. Recharge adds water to the aquifer and pumpage removes water from the aquifer.

The term aquifer stresses in this report refers to sources or sinks of water that are not functions of the water level in the aquifer. These sources or sinks add or subtract water from the aquifer. In the ground-water flow equation, aquifer stresses are frequently represented by the term W (McDonald and Harbaugh, 1988, p. 2-1). The only two aquifer stresses discussed in this section are recharge and pumpage.

Recharge

Recharge was water added to the aquifer as a result of precipitation and as a result of various human activities. The various components of recharge input to the model are discussed below. They are rangeland recharge, surface water irrigation recharge, dryland recharge, and ground-water irrigation recharge. These various components were tracked separately during model construction and calibration, but were added together before the model was run.

Rangeland recharge

Rangeland recharge (fig. 14) was the only recharge considered in the pre-canal period numerical model. Rangeland recharge was computed by The Flatwater Group and was provided as input to the model. This recharge was computed using a regionalized soil-water balance model with daily meteorological conditions for 1953-2010. The model used three different soil types and assumed that the entire area was in grassland. The output from CropSim was post-processed by The Flatwater Group to account for runoff and actual grassland evapotranspiration and to get the results into the model grid. The

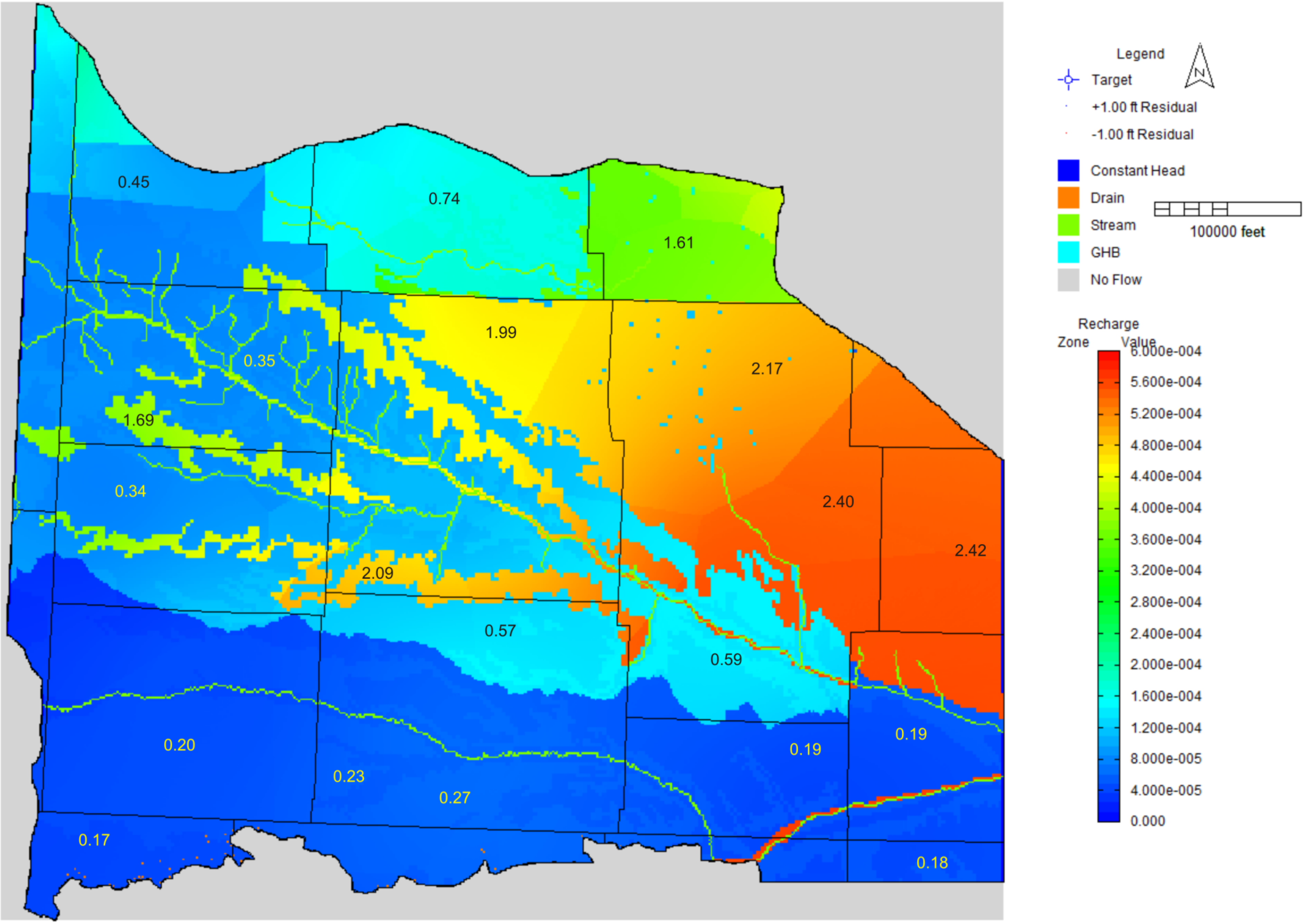


Figure 14. Rangeland recharge used in the calibrated model. Units on map are inches per year and units in legend are feet per day.

rangeland recharge for 1953-2010 was averaged to get an average annual value per model cell for the pre-canal period model. Beginning in 1895, average seasonal values were used in the model. For the period prior to 1953, this recharge was 540,000 acre-feet per year.

Rangeland recharge ranged from 0.10 in/yr to 2.5 in/yr. The smallest recharge occurred in the western part of the model, especially in Laramie County, Wyoming, and Banner County. Recharge was slightly larger in much of western Kimball County and adjacent areas. Recharge was also small around the southeastern part of the study area. Soils in this area are heavier (more clay with greater water-holding capacity) which reduces recharge. Recharge in much of the rest of the Cheyenne Tableland was 0.20 to 0.30 in/yr or 0.50 in/yr to 1.0 in/yr. The boundary between these areas in northern Cheyenne County and southern Garden County is on the drainage divide between the North Platte basin and South Platte basin. This boundary is an artifact of how recharge was computed. One parameter was based on drainage basins and this parameter caused computed recharge to change on the drainage basin boundary.

Recharge in Pumpkin Creek valley and much of North Platte valley was 0.30 to 0.50 in/yr. Recharge was higher on Wildcat Hills, the south escarpment of Pumpkin Creek valley, and the north escarpment of North Platte valley. This is because soils in these areas are lighter (sandier with less water holding capacity) which increases recharge. Recharge was also higher because lighter soils along the channels of the North Platte River and South Platte River.

Recharge on the Alliance Tableland and in the northwest part of the study area was 0.50 to 1.0 in/yr. The straight-line boundaries between the recharge zones in this area is also an artifact on how recharge was computed.

Recharge in the Sand Hills was much higher because of the light soils and a poorly developed drainage system. Recharge increased from west to east because precipitation increased from west to east.

Rangeland recharge from the pre-canal period model was continued at the same rate into the pre-ground-water development period and the ground-water development period. However, rangeland recharge was applied to a smaller area during ground-water development period and variable monthly values rather than long term average values were used.

Surface Water Irrigation Recharge

Surface-water irrigation recharge consists of three components, canal leakage recharge due to canal loss, lateral leakage recharge due to lateral loss, and recharge due to deep percolation of water on irrigated fields. These components of recharge were estimated individually by Mark Mitisek (Leonard Rice Engineers, Inc., "WWUM_Final_Cell_Conveyance_Loss_051320.txt" and Kara Sobieski (Wilson Water

Group, "Western Water Use Management Model Historical Crop Consumptive Use Analysis," November 2012) and then combined for input into the model. The estimates were based on the surface-water model being developed concurrently with the ground-water model in this study. This recharge was added to the ground-water flow model beginning in 1895.

Canal and lateral leakage was calculated by multiplying historical monthly canal diversion by conveyance efficiency. Conveyance efficiencies were tabulated by Kara Sobieski in "Western Water Use Management Model Historical Consumptive Use Analysis" (November 2012) and came from U.S. Bureau of Reclamation, Bishop-Brogden Associates Inc. (2002), Leonard Rice Engineers, Inc., and Derrel Martin (University of Nebraska - Lincoln). Conveyance efficiencies ranged from 45 percent to 72 percent and tended to be higher for shorter canals.

Canal and lateral losses were partitioned between canals and laterals with 83 percent of the loss assigned to the canal and 17 percent assigned to laterals. If a canal had no laterals, 100 percent of the loss was assigned to the canal.

Along each canal, losses were partitioned in one of three ways. For Interstate Canal and Tri-State Canal, losses were partitioned based on Nebraska Department of Natural Resources seepage runs (Jesse Bradley, Nebraska Department of Natural Resources, electronic commun., February 1, 2012), with apparent canal gains ignored. For 14 larger canals where data were available, U.S. Geological Survey leakage potential factors based on geophysical data (Ball and others, 2006; Burton and others, 2009; Vrabel and others, 2009) were used. Each canal cell was assigned a weight based on the area weighted leakage potential computed from geophysical data. Loss assigned to a canal cell was total canal loss times cell weight divided by the sum of the canal cell weights. For the remainder of the canals (primarily smaller canals), losses along the canal were partitioned based on the length of the canal within each model cell, with segments shorter than 500 ft ignored.

Within laterals under a canal, losses were partitioned based on simulated saturated thickness in the ground-water model in December 2011. Lateral cells with greater than 20 ft saturated thickness were assigned twice the loss as lateral cells with less than 20 ft saturated thickness.

Recharge due to deep percolation of water on irrigated fields also was estimated by Kara Sobieski (Wilson Water Group, "Western Water Use Management Model Historical Crop Consumptive Use Analysis," November 2012). This recharge accounted for recharge due to over application of surface water. Over application is essential in flood irrigation to get water to the lower edge of the field. Even in sprinkler application, over application is needed to provide water to crops and to prevent a buildup of salts in the soil. This recharge also accounted for recharge due to precipitation on recently irrigated fields. After a field is irrigated, the soil profile is full of water. If precipitation falls on a field whose soil profile is full, this precipitation causes water to move out of the bottom of the soil profile and ultimately become recharge. Even if the soil profile is not full, the precipitation may be sufficient to fill the soil profile and additional precipitation causes recharge.

Figure 15 shows 1953-2010 average irrigation season recharge. Surface-water irrigation recharge dominates this average recharge and occurs mostly in the North Platte valley although there is some surface-water irrigation recharge in Blue Creek valley, Pumpkin Creek valley, and South Platte valley. Recharge is greatest along canals with lesser amounts occurring along laterals. Recharge from deep percolation of applied surface water also accounts for substantial recharge.

Recharge from canal leakage along Interstate Canal (northwestern most canal in figure 15) is as large as 250 inches per season, but values around 80 inches per season are more typical. Recharge from canal leakage along Ft. Laramie Canal (southwestern most canal in figure 15) ranges from 30 to 50 inches per season. Recharge from laterals off of Interstate Canal ranges from 7 to 14 inches per season while recharge from laterals off of Ft. Laramie canal is about 8 inches per season.

Dryland Recharge

Dryland farming can cause recharge to be greater than rangeland recharge. Dryland farming, as practiced in the study area, seeks to increase soil moisture for later use by crops. Winter wheat is the dominate dryland crop in the area. It is planted in the fall and harvested early the next summer. Following harvest, the field is left fallow for a year or more so that precipitation may build up soil moisture for a subsequent crop. During the fallow period, the field is cultivated or chemicals are used to eliminate vegetation and create a barrier against evaporation from the soil. If soil moisture is built up to field capacity and additional precipitation falls, this precipitation causes recharge to occur. This may only happen infrequently, but the area in dryland farming is large, so this recharge can be substantial.

Dryland recharge was not added to the numerical model for the period 1895-1953 because there were no observation wells in the study area during this period that were capable of detecting this recharge. Extra recharge may or may not have occurred during this period.

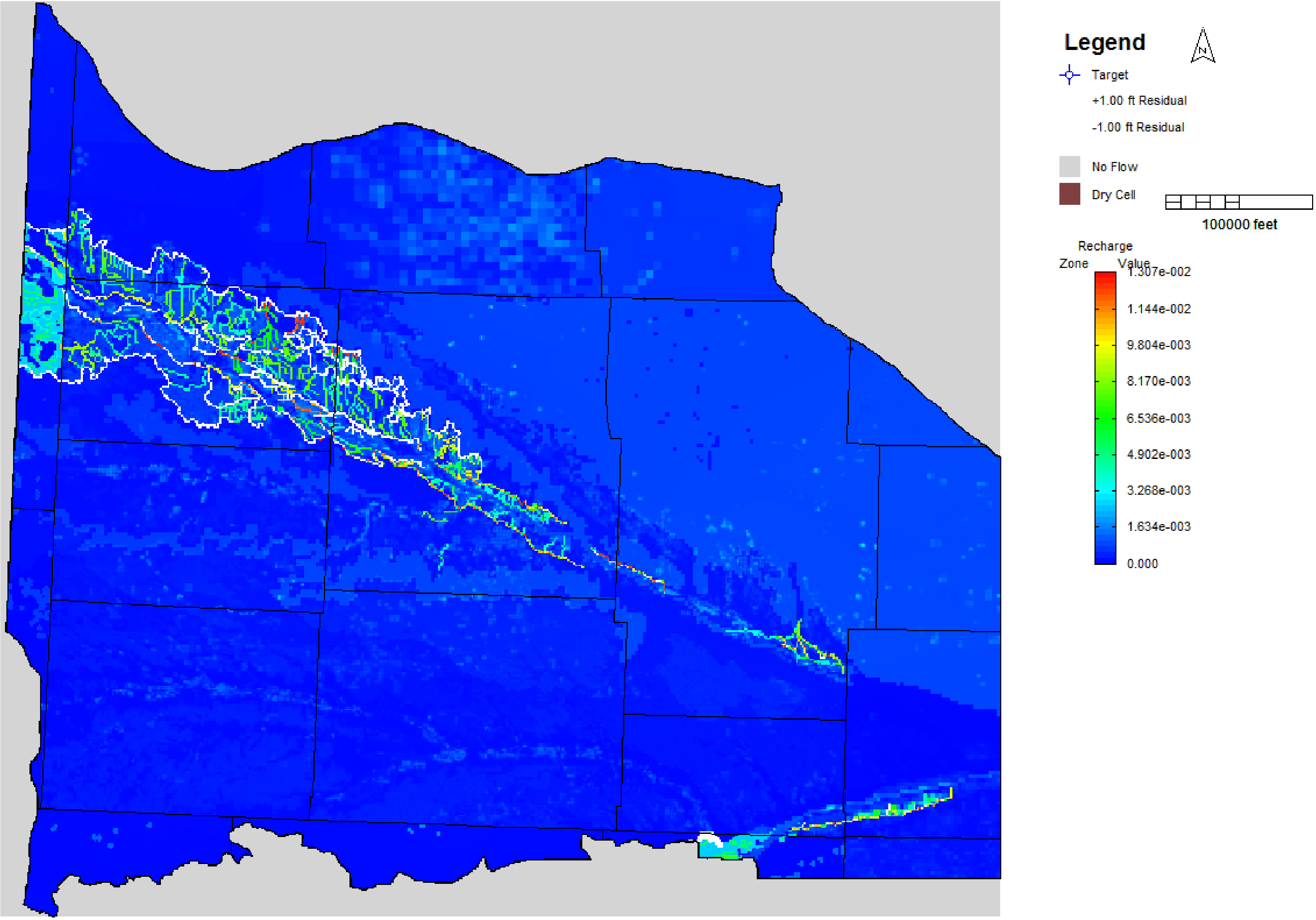


Figure 15. Average 1953-2010 irrigation season recharge used in the calibrated model. Units are feet per day. Upper limit is set to 0.01307 ft/d (2 ft per season), so cells with recharge greater than this value are white.

Beginning with the ground-water development period model, recharge due to dryland agriculture was added to the model. Dryland recharge was computed by The Flatwater Group and was provided as input to the model. Recharge was computed using CropSim daily water balance model, three soil types, estimated crop types, and meteorological conditions for 1953-2010. Fallow fields was one of the crop types accounted for in this analysis. The results from CropSim were post processed by The Flatwater Group to distribute the recharge to model cells, account for real dryland crop evapotranspiration, and account for runoff from the edge of the fields.

Ground-Water Irrigation Recharge

Ground-water irrigation also causes recharge. This recharge was added to the model beginning in 1953. This recharge was from over application of ground water, leakage from small ditches when that was the way water was delivered to the field, and recharge due to precipitation when it fell on recently irrigated fields.

Ground-water irrigation recharge was computed by The Flatwater Group and was provided as input to the model. Recharge was computed using CropSim daily water balance model, three soil types, estimated crop types, and meteorological conditions for 1953-2010. CropSim also estimated net irrigation requirement and applied water to the field as needed as part of the simulation. The results from CropSim were post processed by The Flatwater Group to distribute the recharge to model cells, account for real crop evapotranspiration, and account for runoff from the edge of the fields.

Recharge from ground-water irrigation also included recharge from precipitation that fell on irrigated fields. Precipitation that fell prior to irrigation increased soil moisture, reduced the net irrigation requirement on the field, and may or may not have caused recharge. Precipitation that fell after irrigation increased the soil moisture beyond field capacity and became recharge.

Pumpage

Pumpage was water removed from the aquifer using wells. Four components of pumpage were added to the model. These include pumpage for irrigation, pumpage for municipal use, pumpage for industrial use (including feed yards), and pumpage for domestic use. These components were tracked separately but were added together before being input into the model. Other components of pumpage, such as rangeland stock use, were assumed to be small and dispersed and were ignored in the model. Calculation of pumpage is described in the Conceptual Flow Model section of this report.

Pumpage was considered only in the ground-water development period of the model, which began in 1953, although it certainly occurred before then. Pumpage has been monitored or accurately reported only in more recent times and had to be estimated for much of the period of the model.

Pumpage for irrigation, municipal use, industrial use, and domestic use was considered in the model. Pumpage for stock use (other than feed lots) and rural domestic use was small and widely scattered and was ignored in the model.

Irrigation Pumpage

Pumpage for irrigation was by far the largest component of pumpage. Up gradient from the canals, pumpage is the only source of irrigation water. Some areas below canals may not have a right to canal water and in these areas pumpage is also the only source of irrigation water in these areas. In areas with access to canal water, pumpage may also occur to supplement canal water or as a convenience for the irrigator. This supplemental pumpage, called commingled pumpage, has increased in more recent times.

Pumpage for irrigation was estimated external to this modeling effort by Leonard Rice Engineering and The Flatwater Group. Irrigation pumpage was estimated based on irrigated acreage, crop type, crop irrigation requirement, irrigation efficiency, and well location.

Leonard Rice Engineering prepared annual maps of irrigated land for 1953-2010 using certified acreage from North Platte Natural Resources and South Platte Natural Resources District; aerial imagery for 1953, 1975/77, 1984, 1993, 1999, 2003, 2005, and 2010; and other information. Specific wells were assigned to each irrigated parcel so that pumpage could be estimated on a well-by-well basis.

The Flatwater Group estimated crop irrigation requirement on a monthly basis using a regionalized soil water balance model that used soil properties, farming practices, crop characteristics, and daily meteorological data. The regionalized soil water balance model used reference crop evapotranspiration calculated using the Hargreaves method. Crop irrigation requirement was calculated as crop evapotranspiration minus effective precipitation minus available soil water. Crop water requirement, combined with yearly crop maps provided by Leonard Rice Engineering and estimated irrigation efficiency was used to estimate irrigation pumpage by well.

To convert crop irrigation requirement to pumpage, an irrigation efficiency needs to be applied. For flood irrigation, an irrigation efficiency of 65 percent was assumed for all times. For sprinkler irrigation, an irrigation efficiency of 70 percent was assumed for 1953-75 and an efficiency of 85 percent was assumed for 1995-2010. For 1975-95, irrigation efficiency was assumed to be a linear interpolation between 70 percent and 85 percent.

Irrigation pumpage from outside North Platte Natural Resources District and South Platte Natural Resources District was obtained from other studies. Pumpage for Arthur, Grant, Keith, and Perkins Counties was obtained from the ongoing Cooperative Hydrology Study. Pumpage for Box Butte and Sheridan Counties was obtained from the ongoing Upper Niobrara-White modeling study conducted by Nebraska Department of Natural Resources. Pumpage for Colorado was obtained from South Platte Decision Support System developed by the state of Colorado (WWMU Technical Memorandum, Colorado Pumping and Recharge Estimates, November 20, 2012). Pumpage for Wyoming was extrapolated from data developed for Wyoming State Engineer and Wyoming Water Development Commission as part of an interstate suit between Wyoming and Nebraska (WWUM Technical Memorandum, Wyoming Ground Water Only Pumping and Recharge Estimates, December 5, 2012).

Irrigation pumpage was the dominant pumpage in the model. For the entire model area, irrigation pumpage ranged from 103,900 acre-feet in 1957 to 1,037,000 acre-feet in 2002. In 2010, irrigation pumpage was 466,700 acre-feet and was 95.0 percent of all pumpage.

Municipal Pumpage

Pumpage for municipal use was estimated based on data provided by North Platte Natural Resources District, South Platte Natural Resources District, Twin Platte Natural Resources District, and Upper Niobrara White Natural Resources District. North Platte Natural Resources District provided baseline net pumpage (actual pumpage minus return flows from treatment plants) for the 12 larger municipalities in the district. Population weighted average per capita net water use for these 12 municipalities was 100,600 gallons per year. South Platte Natural Resources District provided baseline net pumpage for the 10 larger municipalities in their district. Population weighted average per capita water use for these municipalities was 124,000 gallons per year. Upper Niobrara White Natural Resources District provided baseline pumpage for Alliance, which had a per capita water use of 89,400 gallons per year. Twin Platte Natural Resources District provided baseline pumpage for Brule and Ogallala, which had a per capita water use 44,000 gallons per year. Municipal pumpage for town outside of the above districts, including Peetz, and Albin, was assigned a per capita pumpage of 107,000 gallons per year.

Industrial Pumpage

Pumpage for industrial water use was estimated based on the Department of Natural Resources registered well database. The Last Name and the UseID fields were examined to find wells that supplied larger industrial water use. This category was dominated by feed lots and feed lots accounted for 80 percent of all industrial water use in the model. The number of cattle on feed per county was determined from the 2007 Census of Agriculture and a factor of 10.5 gallons per day per head was applied. This water use was then divided evenly among all of the feed lot wells within the county. Water use for the remaining 20 percent of the industrial wells was estimated on an industry-by-industry basis. In 2010, industrial pumpage was 1.0 percent of all pumpage.

Domestic Pumpage

Pumpage for domestic water use was based on Department of Natural Resources registered well database. The UseID field was used to find domestic wells. These wells were then assigned a pumpage of 243,000 gallons per year. In 2010, domestic pumpage was 0.3 percent of all pumpage.

Model Calibration

Model calibration is a process of systematically adjusting selected model inputs within reasonable limits while comparing simulated results to real world results. Real world results in this model calibration include measured ground-water levels and estimated ground-water discharge to streams.

The model was calibrated in two phases. The first phase was to calibrate the model for the period before large scale development of the aquifer for irrigation. This was set as the period before May 1, 1953. This was called the pre-ground-water development period calibration. The second phase was to calibrate the model for the period after large scale development of the aquifer for irrigation. This period began May 1, 1953 and ended April 30, 2011.

Model Calibration Targets

The ground water-level targets used for calibration frequently had measured spring and fall measurements over a number of years but some of the targets may have consisted of only a single measurement. These targets were weighted in a manner that reflects not only the accuracy of the measurements but also the value of the target in calibrating the model.

Stream baseflow targets used for calibration were based on gaging station records. These records were used to generate monthly baseflow targets. Many gages had long term records, so targets were available for much of the calibration period.

Ground-Water Level Targets

Ground-water level targets for this study were provided by Thad Kuntz (Adaptive Resources, Inc.). He provided water-level targets for both the pre-ground-water development period model and the ground-water development period model. Kuntz also provided weights for each target. These targets were then culled and processed as described below.

Pre-ground-water level targets were selected from the USGS database that represented the state of the system prior to large scale ground-water development. The earliest measurements were in 1907 and the latest measurements representing pre ground-water development conditions were in 1965. The original measurements are stored in shapefile WL_target_111122.

The original dataset of potential targets contained 1509 points. Several criteria were used to eliminate points not useful for calibration. Three points were outside the active grid or were too close to the edge of the grid to calculate a simulated water level. There were 83 points without a reported elevation in the database and these were eliminated. There were 95 points where the elevation in the database differed from the Digital Elevation Model by more than 50 ft and these were eliminated. There were 27 points where the water-table elevation differed from the trend of surrounding points by more than 50 ft and these were eliminated. There were 17 points not in the High Plains aquifer and these were eliminated. That left of total of 1284 water-level point targets. Some points may have met more than one elimination criterion, but they were eliminated in the order indicated.

In some areas of the model, there were numerous targets, all representing essentially the same hydrologic conditions. To correct this problem, the targets were culled such that the targets were at least 3 mi apart. This reduced the number of pre-ground-water development period water-level targets to 297 without substantially reducing the amount of information available for calibration.

Although the water-level targets spanned a number of years and all seasons, all targets were compared to simulated May 1, 1953 water levels. This was reasonable because outside the surface-water irrigated areas, aquifer stresses were held constant for the period 1895-1953. Inside the surface-water irrigated areas, aquifer stresses changed between the irrigation season and the non-irrigated season, but were the same for every irrigation season and every non-irrigation season.

Ground-water level targets for the ground-water development period model were selected from sites in the USGS database that had at least five measurements. The original dataset of potential water-level targets for the ground-water development period model contained 1010 sites with a total of 22,571 measurements. The points were stored in shapefile WL_1953-2011_120530a.

The original dataset was checked with the same criteria as described above. After these criteria were applied, 877 sites with a total of 21,134 measurements remained. From this dataset, sites with at least 25 measurements for 1953-2011 were selected and the points were further culled such that the targets were at least 3 mi apart. This left 131 targets with a total of 8,290 measurements while maintaining a reasonable distribution of targets.

Stream Baseflow Targets

Stream baseflow targets for this study were provided by Jesse Bradley (Nebraska Department of Natural Resources). He provided stream baseflow targets for both the pre-ground-water development period and the ground-water development period model. Stream baseflow is defined as ground water discharged to hydraulically connected streams and is what maintains streamflow between periods of precipitation. One characteristic of stream baseflow is that it tends to change slowly over time.

Most streams in the study area are highly regulated and this regulation makes it difficult to estimate baseflow. Regulation includes diversions from streams and returns of diverted water to streams. Several methods were tested to estimate baseflow and the pilot point method proved most satisfactory. This method worked best on tributary streams that were gaged year around.

In the pilot point method, stream baseflow is estimated using expert judgment during times of steady streamflow. These estimates are called pilot points. The pilot points are connected using a smooth line to estimate baseflow at other times. In this study, pilot points were typically spaced 2 months apart.

Baseflow can be better estimated during the fall and winter when there typically is little regulation of the stream. During the summer, there may be diversions from the stream, which may decrease steady flow of the stream, or there may be runoff to the stream from surface-water irrigation, which may increase steady flow to the stream.

Some tributary streams were gaged only during the irrigation season. Because these streams carry irrigation runoff in addition to baseflow during the irrigation season, it is very difficult to estimate baseflow to these streams.

For the North Platte River, stream baseflow gain was estimated using reach gain data. Reach gain was calculated as flow at the downstream gage minus flow at the upstream gage minus any diversion between the gages. Reach gain data requires streamflow estimates at two or more points and thus introduces more potential error into baseflow estimates.

Stream baseflow was estimated on a monthly basis for the period 1953-2006 for most stations. Only streamflow data through 2006 were available when the estimates were made,. For some stations, streamflow data were not available for the early period, so baseflow estimates were not made.

Pre-Ground-Water Development Period Calibration

Several model inputs were adjusted in the pre-ground-water development period model. The model inputs were adjusted iteratively, with one model input being adjusted and then another adjusted in a later iteration. Some model inputs, such as hydraulic conductivity, rangeland recharge, and streambed conductance being adjusted several times. These inputs are discussed in their general importance in model calibration.

Hydraulic Conductivity

Hydraulic conductivity was originally estimated based on lithology of test holes but was modified substantially during model calibration. Hydraulic conductivity was modified so that simulated water levels better fit observed water levels. Figure 12 shows the final hydraulic conductivity distribution.

The values for hydraulic conductivity in the North Platte valley were adjusted during calibration although the distribution was not dramatically changed. The values in the valley south of the North Platte River were increased substantially and the values north of the river were decreased. The shape of the hydraulic conductivity polygons were altered primarily along the northern and southern edges of the valley.

Hydraulic conductivity was modified during calibration in the northeastern part of the model in Sheridan County, northern Garden County, and eastern Box Butte County. These modifications were made primarily to fit water-level targets in Box Butte County. These modifications were made in areas of sparse test hole data.

The hydraulic conductivity distribution in the southern half of the model was altered during calibration as data from test holes were reevaluated. The predominant feature in this area is the "flying angle" in northern Cheyenne County and adjacent areas. The shape of this feature was modified and extended during calibration in order to better match observed water levels.

Hydraulic conductivity in Lodgepole valley and its tributary Sidney Draw was increased during calibration. This was done in order to better match numerous observed water levels in the area.

Hydraulic conductivity was increased in various paleovalleys in the model during calibration. These are discussed in a later section.

Rangeland Recharge

Prior to calculation of rangeland recharge by The Flatwater Group, rangeland recharge was estimated using soil type and topographic regions. This recharge resulted in satisfactory simulated water levels but was not based on actual meteorological conditions.

The Flatwater Group provided several versions of rangeland recharge for the model. Each version was tested using the model and simulated water levels were compared to observed water levels. Feedback was then provided to The Flatwater Group indicating where the model needed more recharge or less recharge. This feedback was based on both observed water levels and baseflow to streams. This feedback included providing The Flatwater Group with the recharge map previously used.

During early simulations, rangeland recharge from The Flatwater Group was averaged over 1953-72 to be consistent with what was done for surface water recharge. This resulted in too much recharge, especially in the southwestern part of the model. When The Flatwater Group noted that 1957 was an especially wet year that affected the average, the recharge was averaged over 1953-2010. When this recharge proved too large, The Flatwater Group adjusted post-processing parameters and computed a new recharge.

Figure 14 shows rangeland recharge used in the final calibrated model. This map was discussed in some detail in the Aquifer Stresses section.

Streambed Conductance

Streambed conductance was not changed until late in the calibration process. Streambed conductance was modified primarily to adjust the simulated fall-to-spring baseflow amplitude to better match observed conditions. The fall-to-spring baseflow amplitude tended to increase as streambed conductance increased. Overall simulated baseflow was not particularly sensitive to streambed conductance.

Table 2 shows streambed conductance used in the final calibrated model. Streambed conductance is 1.0 ft/d per foot of length for Lodgepole Creek and Pumpkin Creek, which flow over fractured Brule

Formation. Conductance is also 1.0 ft/d per foot for several smaller streams. Streambed conductance is 20 ft/d per foot for North Platte River and South Platte River, the largest streams in the study area. Conductance ranges between these two values for the rest of the streams in the study area.

Table 2. Streambed conductance, in feet per day per linear foot. Not all streams are labeled in figure 1 but are included here for completeness.

Name	Conductance
Akers Draw	10.0
Alliance Drain	10.0
Bald Peak Drain	10.0
Bayard Drain	10.0
Blue Creek	5.0
Cedar Creek	10.0
Clear Creek	1.0
Coldwater Creek	10.0
Dry Spottedtail Creek	10.0
Dunham Andrews Drain	5.0
Dutch Flats Drain	10.0
Gering Drain	5.0
Greenwood Creek	1.0
Hiersche Drain	10.0
Horse Creek	10.0
Indian Creek	10.0
Kiowa Creek	10.0
Lane Drain	10.0
Lawrence Fork	1.0
Lodgepole Creek	1.0
Lonergan Creek	1.0
Melbeta Drain	10.0
Moffat Drain	10.0
Ninemile Creek	10.0
North Platte River	20.0
Otter Creek	1.0
Owl Creek	10.0
Pumpkin Creek	1.0
Red Willow Creek	5.0
Rush Creek	10.0
Scottsbluff Drain	10.0
Sheep Creek	10.0
Silvernail Drain	10.0
Snake Creek	10.0
South Platte River	20.0
Spottedtail Creek	10.0
Sunflower Drain	10.0
Tub Springs Drain	10.0
Upper Dugout Creek	10.0
Wildhorse Canyon	5.0
Wildhorse Drain	5.0
Winters Creek	5.0

Paleovalleys

Paleovalleys were added to the model during the pre-ground-water development period calibration. Paleovalleys are valleys cut into the base of aquifer surface prior to deposition of the High Plains aquifer. Paleovalleys have long been suspected in the study area, but their narrow width make them difficult to detect. They are thought to be from a few hundred to a few thousand feet wide, so they are usually missed with test holes spaced miles apart.

Paleovalleys have been mapped in the North Platte valley where high-density geophysical data have been collected along closely spaced lines. This geophysical data then allowed interpretation of test-hole data that had previously been difficult to interpret. Paleovalleys were not added in the North Platte valleys because the base of aquifer already represented these features.

One major paleovalley system was added to the model south of the North Platte valley. This system of paleovalleys can be seen in the hydraulic conductivity map (fig. 12). This system occurs primarily in Kimball and Cheyenne Counties. The southern leg of this system is composed of two tributary valleys that join north of Lodgepole valley. The northern leg of this system also is composed of two tributary valleys that join in northern Kimball County. The two legs of this system then join in central Cheyenne County and head east and north. This system was drawn only as far north as the North Platte valley but may proceed further north and may be part of the Rush Creek Structure (Swinehart and others, 1985).

There were four other paleovalleys added to the model south of the North Platte valley. These paleovalleys are mostly in Deuel and Garden Counties and they have several tributaries.

There were two paleovalleys added to the model north of the north Platte valley. Data are sparse north of the North Platte valley, so other paleovalleys may have been missed. The paleovalley to the east may be a continuation of the paleovalley system south of the North Platte valley discussed previously.

Major paleovalleys in the model were drawn 5/8 mi wide and minor paleovalleys were drawn 3/8 mi wide. These widths were settled upon after several trial-and-run calibration simulations. The classification as to major and minor was a judgment based on calibration.

Paleovalleys were used to do two things in the model. First, the base of aquifer was lowered 200 ft beneath the paleovalleys. Second, hydraulic conductivity was increased to 120 ft/d, except where it was already greater than that.

Ground-Water Development Period Calibration

Most of the calibration was done with the pre-ground-water development period model and the final inputs from that model were used in the ground-water development period model. Only specific yield was changed during calibration of the ground-water development period model.

Specific Yield

Originally specific yield was based on generalized geology, with one value assigned to alluvium, a second assigned to the Ogallala Group, and a third assigned to the Arikaree Group. Specific yield for the Arikaree Group was increased during calibration to better simulate water-level changes in Box Butte County. Elsewhere, specific yield was reduced by 25 percent during calibration to better simulate spring-to-fall change in stream baseflow.

Streams draining the area where surface-water irrigation occurs have increased baseflow in the irrigation season and decreased baseflow in the non-irrigation season. The amplitude of this spring-to-fall fluctuation in baseflow is somewhat sensitive to specific yield in the North Platte valley. Elsewhere, except where there are substantial water-level declines, the model is relatively insensitive to specific yield.

Model Results

Model results are shown for two periods, the pre-ground-water development period and the ground-water development period. The first period ends May 1, 1953 and the second period ends May 1, 2011.

Pre-Ground-Water Development Period Calibration

This section reports the results of the pre-ground-water development period calibration. It reports results on simulated water levels, simulated baseflow to streams, and simulated water budgets.

1953 Potentiometric Surface

Figure 16 shows the simulated 1953 potentiometric surface for the calibrated model. The potentiometric surface is highest in the southwest part of the model where it is more than 5400 ft above sea level in Weld County, Colorado. It slopes to the east and is lowest, less than 3200 ft above sea level, where the South Platte River leaves the study area. Locally, the potentiometric surface has a high in the Wildcat Hills, represented by the complex contours in the figure.

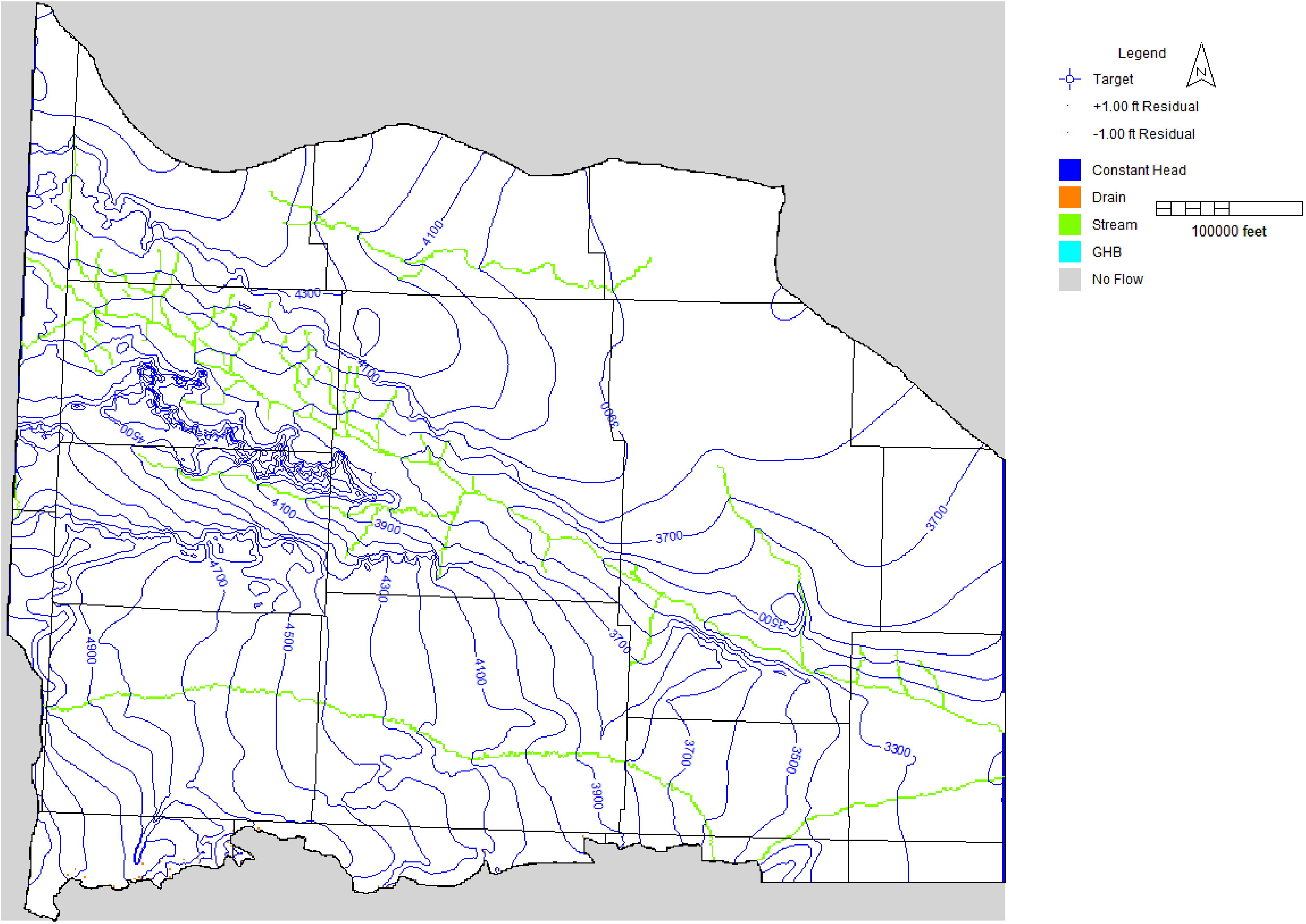


Figure 16. Simulated 1953 potentiometric surface from the calibrated model. Contour interval is 100 ft. Datum is sea level.

In the northwest corner of the study area, the potentiometric surface is more than 4700 ft above sea level and in the northeast corner it is less than 3900 ft. The potentiometric surface slopes toward the North Platte River, Snake Creek, Pumpkin Creek, and parts of Lodgepole Creek. The surface is particularly flat in Sheridan County and northern Garden County.

1953 Water-Level Targets

Figure 17 shows water-level residuals at the 1953 targets. The residuals range from -100 ft to +86 ft. The largest negative residual, -100 ft, is in Pumpkin Creek valley in Banner County. There are 12 residuals less than -50 ft, including four in Cheyenne County, three in Wyoming, two each in Scotts Bluff and Kimball Counties, and one in Banner County. The largest positive residual, +86 ft, is in Kimball County. There are nine residuals greater than +50 ft, including two in Keith County, two in Colorado, two in Wyoming, and one each in Deuel, Kimball, and Sioux Counties. The mean water-level residual for the 297 points was -7.2 ft and the median residual was -7.1 ft.

Table 3 shows water-level residuals for 1953 by group. There are twelve groups that are based on counties or groups of counties. Box Butte County has the largest number of targets and Banner County has the smallest number of targets. The most negative mean residual, -35.3 ft, occurs in Banner County, but this is based on only three targets, one of which has a value of -100 ft. The next most negative mean residual, -16.1 ft, occurs in Cheyenne County. The largest positive residual, 17.3 ft, occurs in Deuel County and is based on nine targets.

The table also shows mean absolute residual, which is the mean of the absolute values of the residuals. The mean absolute residual is useful because it does not allow compensating residuals to cancel each other out. The largest mean absolute residual occurs in Banner County and is based on three targets. The next largest mean absolute residual, 39.7 ft, occurs in Colorado and is based on eight targets. It is interesting to note that Colorado has the smallest mean residual, 0.5 ft. Colorado has both large negative residuals and large positive residuals, which tend to cancel each other out. The smallest mean absolute residual, 11.7 ft, occurs in Garden County and is based on 11 targets. The targets in Garden County are mostly clustered in the Crescent Lakes area and the largest residual in this area, in terms of absolute value, is -34 ft.

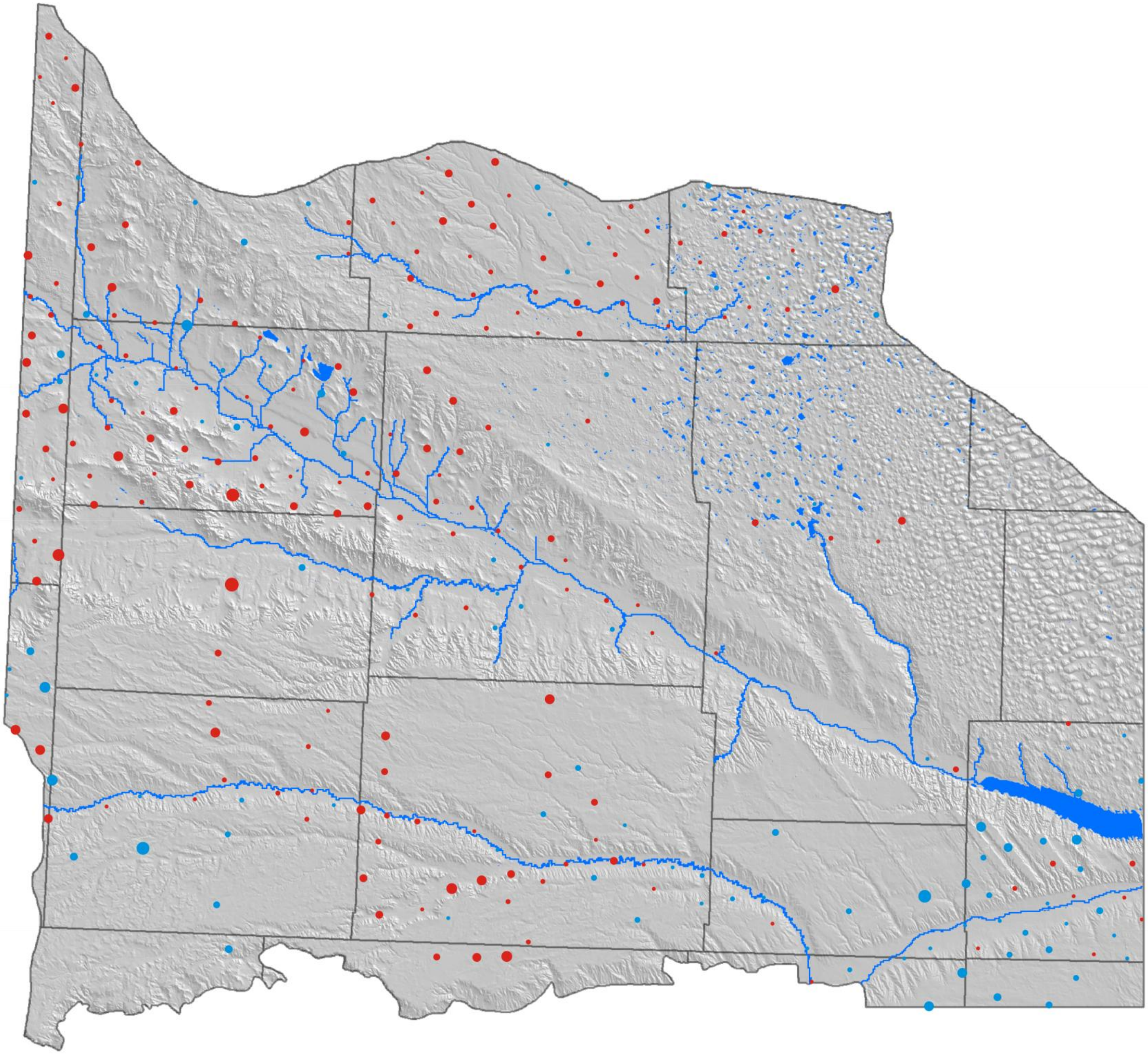


Figure 17. Residuals at 1953 water-level targets. Residuals range from -100 to +86 ft. Negative residuals are red and positive residuals are cyan. Diameter of circle is proportional to absolute value of residual, except minimum diameter is maintained to aid in visibility.

Table 3. 1953 water-level residuals at targets by group. RMS is root-mean-square residual.

Group	Description	Count	Weighted			Unweighted		
			Mean	Mean Abs.	RMS	Mean	Mean Abs.	RMS
1	Sioux County	17	-3.4	14.2	16.9	-5.3	23.6	28.1
2	Box Butte and Sheridan Counties	55	-5.5	7.7	11.4	-10.3	14.3	17.9
3	Scotts Bluff County	45	-4.1	6.1	8.0	-13.8	19.8	26.3
4	Banner County	3	-15.2	20.6	23.6	-35.3	53.3	62.6
5	Morrill County	32	-4.2	5.4	8.1	-10.8	15.2	18.8
6	Garden County	11	-2.1	3.2	4.4	-6.4	11.7	15.3
7	Kimball County	18	-2.1	7.8	12.0	-1.9	22.5	33.2
8	Cheyenne County	34	-5.1	6.9	9.5	-16.1	23.2	29.4
9	Deuel County	9	5.6	5.8	11.8	17.3	19.1	31.4
10	Perkins, Keith, and Arthur Counties	33	3.7	5.0	6.7	14.2	19.3	25.0
11	Colorado	8	-0.5	13.7	15.8	0.5	39.7	45.2
12	Wyoming	32	7.1	9.2	9.5	-12.3	29.2	36.6
	Overall	297	-2.9	7.2	10.4	-7.2	20.6	27.6

1953 Stream Baseflow

Table 4 shows simulated 1952-53 stream baseflow for selected streams in the model. The column "Fall simulated" represents simulated baseflow on October 31, 1952, and the column "Spring simulated" represents simulated baseflow on April 30, 1953. The targets represent estimated baseflow for those same months. Lodgepole Creek at Kimball, Brownson, and Sidney was not gaged during this time and the targets are based on miscellaneous measurements at various times at these sites. Jesse Bradley (Nebraska Department of Natural Resources) was not responsible for these targets.

The simulated baseflows for Kiowa Creek tend to be lower than the target flows, while the simulated baseflows for Horse Creek, Gering Drain, and Pumpkin Creek tend to be higher than the target baseflows. The sum of the simulated fall baseflows for the north side tributaries to the North Platte River (shaded in the table) is nearly the same as the sum of the target fall baseflows. For the spring, the sum of the simulated baseflows is greater than the sum of the targets by about 19 percent. Within this group, the simulated baseflows of Ninemile Creek and Red Willow Creek tend to be high and the simulated baseflow of Winters Creek tends to be low. The remainder of the streams in this group have about the right simulated baseflow.

Table 4. Simulated 1952-53 stream baseflow for selected steams.

Stream	Fall Simulated	Spring Simulated	Fall Target	Spring Target
Kiowa Creek	27.6	28.5	19	6
Horse Creek	61.7	53.1	41	14
Sheep Creek	73.7	62.0	75	61
Dry Spottedtail Creek	25.2	17.1	27	13
Tub Springs Drain	46.2	34.8	49	24
Winters Creek	22.6	17.3	63	34
Gering Drain	41.4	39.0	36	19
Ninemile Creek	94.1	71.4	81	57
Bayard Drain	25.5	15.7	30	18
Red Willow Creek	116.2	84.1	77	48
Pumpkin Creek	41.4	41.0	14	19
Sum of highlighted streams	403.6	302.5	402	255
Blue Creek	84.5	81.6	76	76
Otter Creek	6.7	6.4		
South Platte River	62.4	226.4		
North Platte River (Lewellen)	1,455	1,293		
Snake Creek	0.0	6.2		
Lodgepole Creek (Bushnell)	6.9	10.9	12	14
Lodgepole Creek (Kimball)	3.4	7.3	12	12
Lodgepole Creek (Brownson)	13.7	17.5	1.5	1.5
Lodgepole Creek (Sidney)	17.4	21.2	3	3
Lodgepole Creek (Ralton)	27.1	30.8	7	9
Melbeta Drain	3.0	2.0	12	2
Indian Creek	13.2	12.4	30	5
Upper Dugout Creek	19.6	17.4	24	2
Silvernail Drain	6.1	5.3	18	4

The simulated baseflow of Blue Creek is about 11 percent higher than the target in the fall and about 7 percent higher in the spring. Blue Creek, which drains the Sand Hills, has very steady flows and the target flows for this stream are probably accurate.

The simulated fall baseflows for Melbeta Drain, Indian Creek, Upper Dugout Creek, and Silvernail Drain are lower than the target flows. The simulated spring flows, except for Melbeta Drain, are higher than the target flows. These streams are only gaged during the irrigation season, so it was difficult to pick target flows for these streams.

1952-53 Water Budgets

Figure 18 shows various subregions of the study area for which water budgets were prepared. These subregions were selected for the convenience of the North Platte Natural Resources District and the South Platte Natural Resources District. Table 5 is a cross-reference of subregion numbers and names.

Table 6 shows simulated water budgets for 1952-53 for various subregions of the study area. The sign convention for the table is that negative indicates water entering the aquifer in the subregion and positive indicates water leaving the aquifer in the subregion. Therefore, recharge is negative because it represents water entering the aquifer.

Not all water-budgets components exist for all subregions. For example, "Springs" only exist in subregion 23 (Colorado), so the value for springs is zero for all other subregions. "Wells" is zero for all subregions because ground-water pumpage was not added to the model until after 1953. It is included in this table only for consistency with a later table.

"Streams" is the net accretion from the aquifer to streams in the subregion. It is not the total stream baseflow in the subregion, but is rather the net gain in stream baseflow in the subregion.

"Outflow from subregion" is the net outflow from the subregion and may include both inflows to the subregion and outflows from the subregion. Subregion 7 (Scotts Bluff - Morrill County Overappropriated Area) has a negative outflow, indicating that 87,500 acre-feet per year enters the aquifer in this subregion.

In the water budget, positive "Storage increase" acts as an outflow from the aquifer. Except for subregion 20 (South Platte valley), every subregion has an increase in ground-water storage in 1952-53.

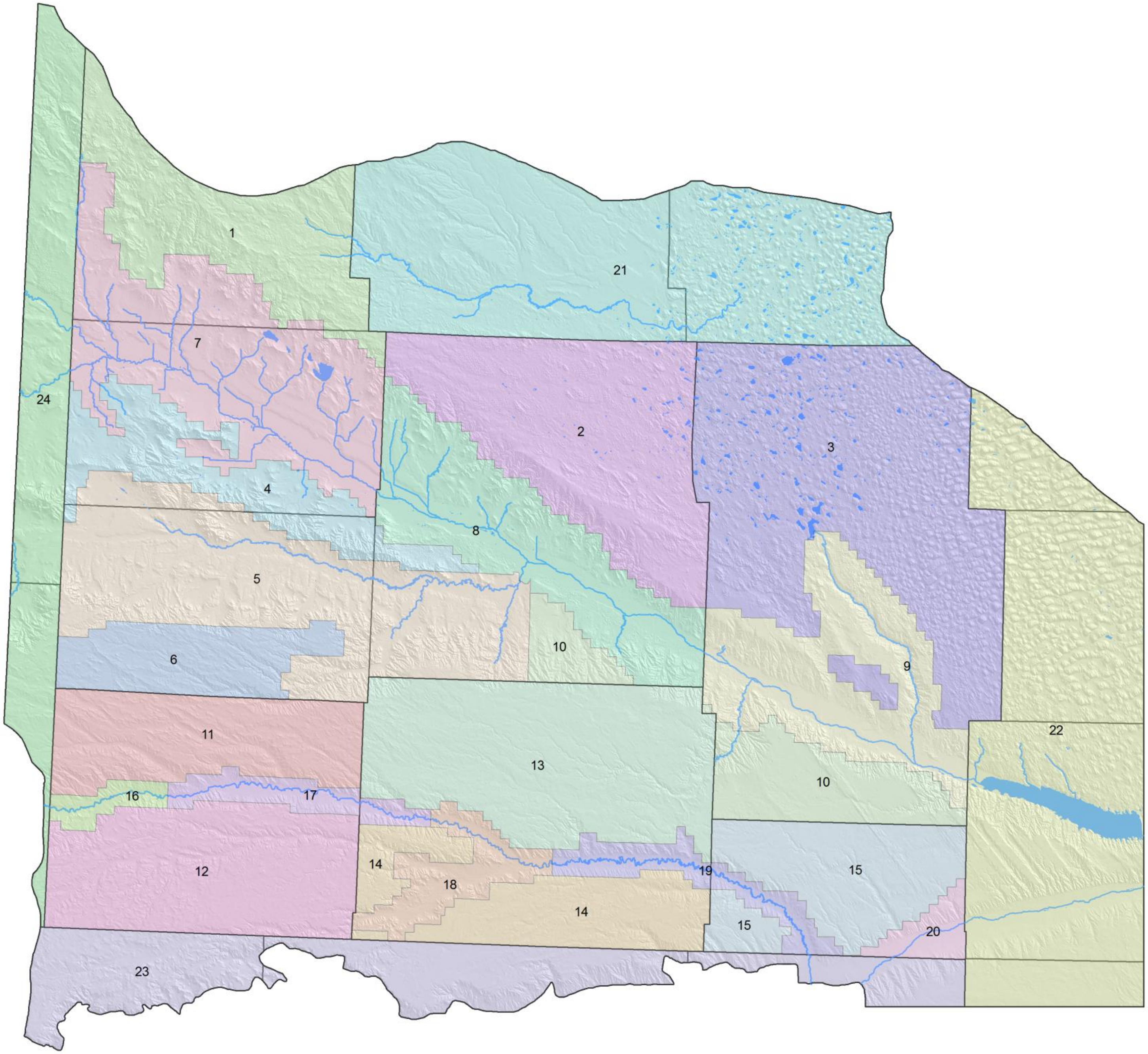


Figure 18. Subregions for which water budgets were prepared. Subregions are named in table 5.

Table 5. Cross-reference of subregion number and name for subregional water budgets. FA is fully-appropriated area and OA is over-appropriated area.

Number	Name	NRD	Acres
1	Scotts Bluff-Sioux FA	NPNRD	274,180
2	Morrill County north	NPNRD	417,612
3	Garden County north	NPNRD	661,032
4	Scotts Bluff-Morrill FA	NPNRD	189,423
5	Pumpkin Creek Basin Management Area	NPNRD	478,388
6	Banner County south	NPNRD	141,640
7	Scotts Bluff-Sioux OA	NPNRD	416,090
8	Morrill County OA	NPNRD	292,865
9	Garden County OA	NPNRD	288,180
10	Garden-Morrill south	NPNRD	191,636
11	Kimball tableland north	SPNRD	219,325
12	Kimball tableland south	SPNRD	312,594
13	Cheyenne tableland north	SPNRD	424,136
14	Cheyenne tableland south	SPNRD	196,400
15	Deuel tableland	SPNRD	212,782
16	Wyoming to Oliver Reservoir	SPNRD	28,603
17	Oliver Reservoir to Buffalo Bend	SPNRD	59,199
18	Buffalo Bend to Sidney	SPNRD	85,770
19	Sidney to Colorado	SPNRD	76,264
20	South Platte valley	SPNRD	35,082
21	Upper Niobrara-White	none	698,147
22	Twin Platte and Upper Loup	none	743,460
23	Colorado	none	362,404
24	Wyoming	none	305,589

Table 6. Simulated water budgets for 1952-53 by subregion. Units are acre-feet per year, except for area, which is acres. Negative values indicate water entering aquifer. Values, except for error, are rounded to nearest 100.

Zone	Area	Recharge	Constant head boundary	Springs	Lakes	Wells	Streams	ET	Outflow from subregion	Storage decrease	Error
1	274,200	-15,300	0	0	0	0	1,400	700	11,100	2,100	-40
2	417,600	-67,000	0	0	0	0	0	26,500	33,300	7,200	-23
3	661,000	-147,800	0	0	0	0	0	73,000	68,100	6,700	-31
4	189,400	-65,700	0	0	0	0	2,800	100	61,900	900	11
5	478,400	-35,700	0	0	0	0	29,400	4,600	-1,200	3,000	102
6	141,600	-7,200	0	0	0	0	0	0	6,100	1,100	-20
7	416,100	-306,700	0	0	6,600	0	377,300	5,100	-87,500	5,200	31
8	292,900	-183,700	0	0	0	0	199,400	8,800	-31,200	6,700	-3
9	288,200	-51,200	0	0	0	0	131,200	3,700	-85,300	1,400	22
10	191,600	-14,200	0	0	0	0	1,900	0	10,800	1,400	-21
11	219,300	-5,900	0	0	0	0	0	0	4,100	1,700	-78
12	312,600	-9,500	0	0	0	0	0	0	5,600	3,800	-139
13	424,100	-21,200	0	0	0	0	0	0	18,200	2,900	-25
14	196,400	-6,500	0	0	0	0	0	0	4,800	1,700	7
15	212,800	-4,600	0	0	0	0	0	0	3,600	1,000	24
16	28,600	-600	0	0	0	0	-1,400	0	1,800	100	-8
17	59,200	-2,000	0	0	0	0	3,000	0	-1,100	200	-17
18	85,800	-2,300	0	0	0	0	6,800	0	-5,100	600	-7
19	76,300	-2,300	0	0	0	0	7,600	0	-5,400	100	-3
20	35,100	-2,100	0	0	0	0	1,300	200	600	0	-3
21	698,100	-75,700	0	0	0	0	8,000	80,200	-17,800	5,300	64
22	743,500	-114,300	58,600	0	32,100	0	16,400	18,100	23,200	11,300	-420
23	362,400	-10,700	0	3,000	0	0	900	200	4,900	1,800	39
24	305,600	-44,800	-2,000	0	0	0	21,700	1,400	23,000	800	-8
Sum		**-1,197,000**	**56,600**	**3,000**	**38,700**	**0**	**807,700**	**222,600**	**100**	**67,000**	-546

Recharge is the largest inflow to the aquifer in the pre-ground-water development period model. This inflow is 1,197,000 acre-feet per year in 1952-53. There is a small inflow to the study area across the western boundary, but this inflow is more than made up by a much larger outflow across the eastern boundary.

Stream baseflow is the largest outflow from the aquifer in 1952-53 and amounts to 807,700 acre-feet. ET is the next largest outflow, but it is about four times smaller than stream baseflow. Increase in storage, which is an outflow in the water budget, is the next largest component, but is nearly four times smaller than ET. Outflow across the eastern boundary is the next largest outflow and amount to 58,600 acre-feet per year.

Within individual subregions, outflow from the subregion, or inflow to the subregion, may be large but the sum of these flows is small because they just represent exchange of water within the study area. Exchange of water with areas outside the study area is represented by budget component "Constant head boundary."

Error represents the error in the water budget and it was calculated before the other values in the table were rounded. The largest error, 602 acre-feet, occurred in subregion 22 (Twin Platte and Upper Loup Natural Resources District). This error is 0.5 percent of the water budget for this subregion. The next largest error, 139 acre-feet, occurred in subregion 12 (Kimball tableland south) and is 1.5 percent of the water budget for this subregion.

The area of the subregion can be useful to normalize the water budget components. This is probably most intuitive for "Recharge" and "Storage increase." As an example, "Recharge" divided by "Area" results in average 1952-53 recharge, in feet, over the subregion. Converted to inches per year, the average 1952-53 recharge for subregion 3 (Garden County north) was 2.68 in/yr and the average 1952-53 recharge for subregion 12 (Kimball tableland south) was 0.36 in/yr. "Storage increase" divided by "Area" for subregion 3 (Garden County north) gives an average increase of 0.01 ft/yr of water. To convert this to water-level rise, it needs to be divided by specific yield (0.135) to get a water level rise of 0.08 ft/yr.

Ground-Water Development Period Calibration

This section reports the results of the ground-water development period calibration. It reports results on simulated water levels, simulated baseflow to streams, and simulated water budgets.

2011 Potentiometric Surface

Figure 19 shows the simulated 2011 potentiometric surface for the calibrated model. This potentiometric surface is similar to the 1953 potentiometric surface. The surface is highest in the southwest part of the model where it is more than 5400 ft above sea level in Weld County, Colorado. It slopes to the east and is lowest, less than 3200 ft above sea level, where the South Platte River leaves the study area. Locally, the potentiometric surface has a high in the Wildcat Hills, represented by the complex contours in the figure.

In the southwestern part of the study area, the 2011 potentiometric surface is similar to the 1953 potentiometric surface. In the southeastern part of the area, one 3200-ft contour is larger and another has appeared south of the South Platte River. The biggest differences are in Sheridan and Box Butte Counties. In the 2011 map, the 3900-ft contour has moved west, from about the Sheridan-Box Butte County line to nearly central Box Butte County. The 4000-ft and 4100-ft contours have also moved west, but to a lesser amount. In some areas, the contours on the 2011 potentiometric surface are not continuous. This is because there are some dry cells in the model and the contours are truncated at dry cells. This can be seen around Sidney Draw and in Sedgwick County south of the South Platte River.

2011 Water-Level Targets

Figure 20 shows water-level residuals at the 2010-11 targets. There were 85 sites where water levels were measured between May 1, 2010 and May 1, 2011. The residuals range from -71 ft to +94 ft. The largest negative residual, -71 ft, is in Sidney Draw in Cheyenne County. There are five residuals less than -50 ft, including four in Cheyenne County and one in Banner County. The largest positive residual, +94 ft, is in Garden County. There are five residuals greater than +50 ft, including two in Box Butte County, and one each in Cheyenne, Garden, and Kimball Counties. Only one of these residuals was greater than +65 ft. The mean water-level residual for the 85 points was +2.5 ft and the median residual was +0.7 ft.

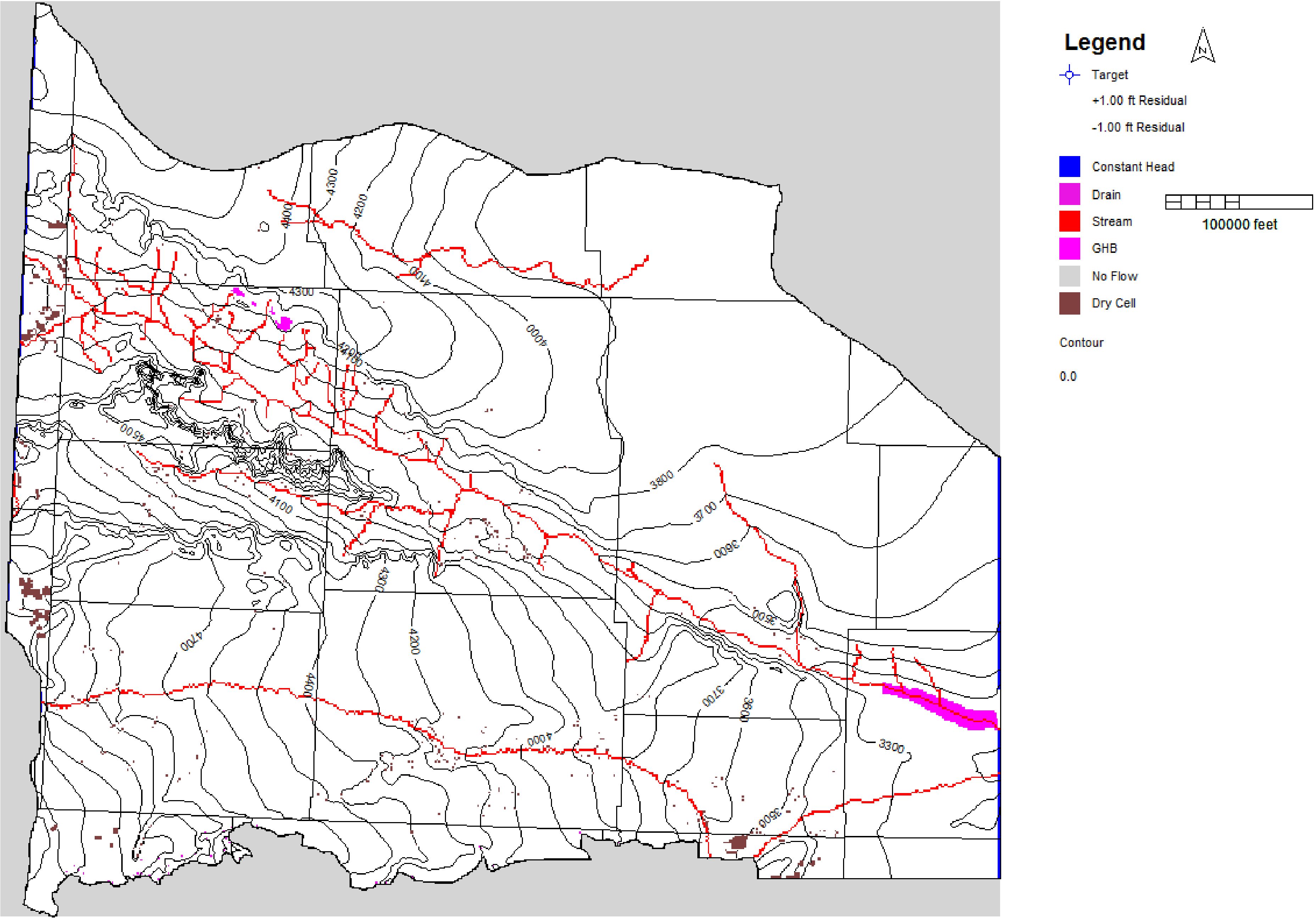


Figure 19. Simulated 2011 potentiometric surface from the calibrated model. Contour interval is 100 ft. Datum is sea level.

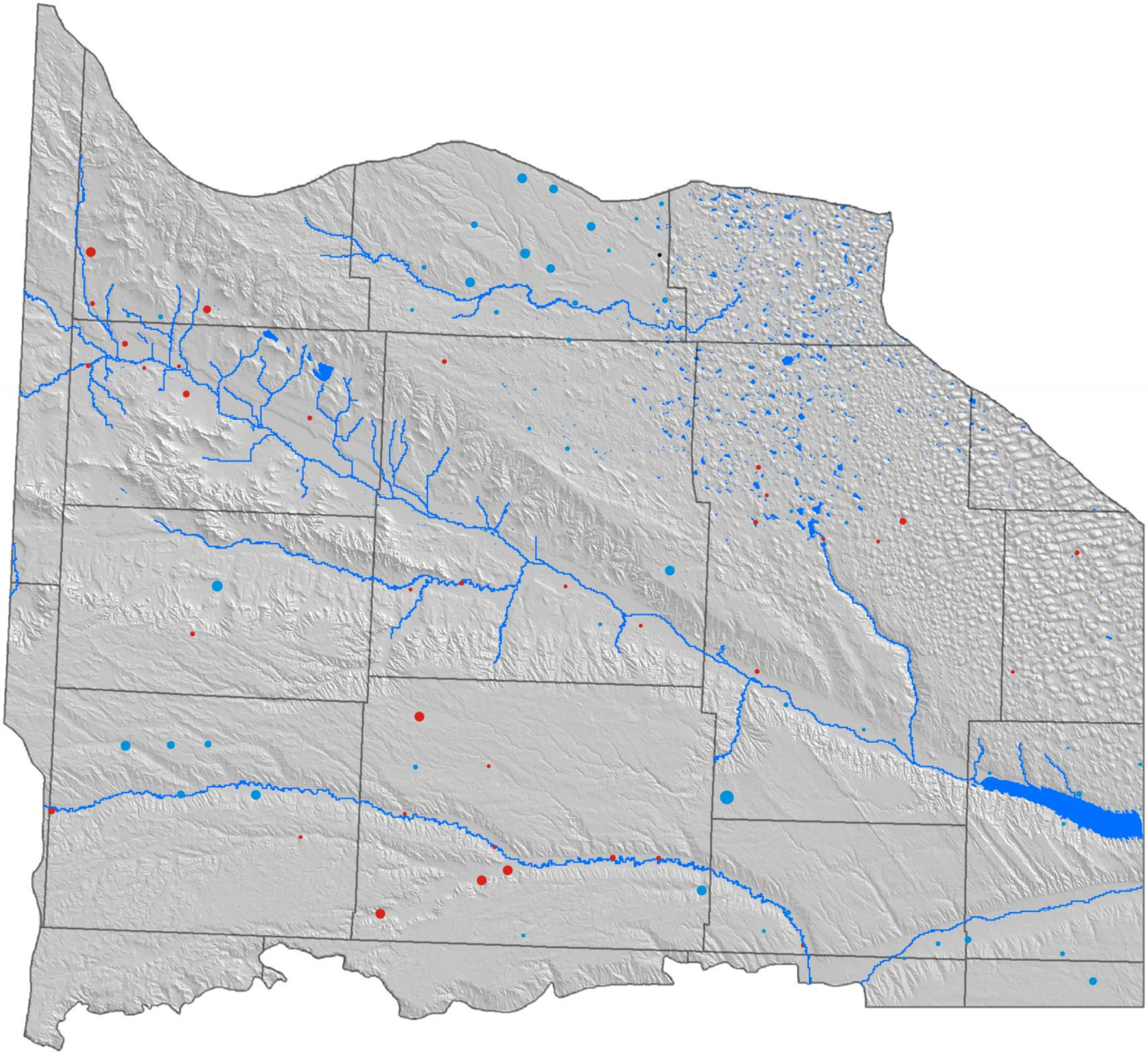


Figure 20. Residuals at 2011 water-level targets. Residuals range from -71 to +94 ft. Negative residuals are red and positive residuals are cyan. Diameter of circle is proportional to absolute value of residual, except minimum diameter is maintained to aid in visibility.

1953-2011 Water-Level Targets

Table 7 shows water-level residuals for 1953-2011 by group. There are twelve groups that are based on counties or groups of counties. There is a total of 8,290 measurements at 131 sites. Garden County has the largest number of measurements, primarily around Crescent Lakes, and Banner County has the smallest number of measurement in Nebraska, although Colorado has only 83 measurements. The most negative mean residual for a group, -23.9 ft, occurs in Scotts Bluff County, although Wyoming and Sioux County are close behind. The largest positive mean residual, +9.1 ft, occurs in Kimball County. The smallest mean absolute residual for the Nebraska groups is 5.4 ft for Deuel County and the largest is 25.4 ft for Sioux County. For all measurements, the mean residual is -4.6 ft and the mean absolute residual is 17.0 ft.

Figure 21 shows mean 1953-2011 water-level residuals. There were 131 sites where water levels were measured between May 1, 1953 and May 1, 2011. At these sites, the mean residual for all the measurements was computed. The mean residuals range from -99 ft to +85 ft. The largest negative residual, -99 ft, is in Laramie County, Wyoming. There are five mean residuals less than -50 ft, including two in Cheyenne County and one each in Banner, Laramie, and Scotts Bluff Counties. The largest positive residual, +85 ft, is in Garden County. There are three mean residuals greater than +50 ft, including one each in Cheyenne, Kimball and Garden Counties. The mean water-level residual for the 131 points was -4.2 ft and the median residual was -1.5 ft.

1953-2011 Water-Level Hydrographs

Figure 22 shows simulated and observed 1953-2011 water levels for four selected targets. The number above the graph is the U.S. Geological Survey Site ID, a unique number identifying the site in their database.

Site 413716103322001 is in Banner County just south of Pumpkin Creek. It has a mean residual of +0.9 ft. In the early part of the record, the simulated water level tracks the observed water level. Beginning in 1983, the observed water level rises while the simulated water level declines. In the 1990s, the simulated water levels somewhat parallel the observed water levels, but are about 10 ft lower.

Site 413216102520201 is in Morrill County south of the North Platte River. It has a mean residual of +8.9 ft. The simulated water level does not track the observed water particularly well. The observed water level declines through about 2004 while the simulated water level is fairly stable. After that, the simulated water levels somewhat parallel the observed water levels, but are about 7 ft lower.

Table 7. 1953-2011 water-level residuals at targets by group. RMS is root-mean-square residual.

Group	Description	Count	Weighted			Unweighted		
			Mean	Mean Abs.	RMS	Mean	Mean Abs.	RMS
1	Sioux County	221	-10.3	11.7	14.2	-22.4	25.5	29.9
2	Box Butte and Sheridan Counties	1,291	-3.5	12.6	16.0	-4.6	19.3	23.8
3	Scotts Bluff County	540	-10.3	10.3	13.3	-23.9	23.9	27.9
4	Banner County	237	-1.2	8.0	13.6	-1.9	14.8	24.8
5	Morrill County	960	1.9	4.6	8.0	2.6	8.8	13.4
6	Garden County	1,739	-2.5	6.8	12.2	-3.3	10.6	18.5
7	Kimball County	574	5.2	10.0	14.2	9.1	17.2	23.4
8	Cheyenne County	798	-9.2	17.7	23.5	-15.1	29.1	36.6
9	Deuel County	219	0.2	2.6	3.1	0.6	5.4	6.5
10	Perkins, Keith, and Arthur Counties	1,190	4.3	8.4	10.6	5.9	12.3	15.0
11	Colorado	83	-7.6	7.6	9.9	-15.7	15.7	20.1
12	Wyoming	438	-12.3	20.3	26.8	-22.4	38.2	45.0
	Overall	8,290	-2.5	10.0	15.0	-4.6	17.0	24.2

Site 414255102200701 is in Garden County just northeast of Blue Creek. It has a mean residual of -1.5 ft. The observed water level is fairly stable, staying in the range 3793-98 ft while the simulated water level has slightly more variability to it. The simulated water level starts out about 5 ft above the observed water in 1953 and then declines to about the observed water level by 1960. It then rises above the observed level, declines, and by 1980 is below the observed level. Beginning in 1995, the simulated water levels track observed water levels fairly well.

Site 411349103455201 is in central Kimball County in Lodgepole valley. It has a mean residual of 14.3 ft. The simulated and observed water levels are close to each other in 1954, but diverge soon after that. Both show a water-level decline over time, but the simulated values decline much more than the observed values. The simulated water level decline to 2011 is 40 ft, while the observed decline is only 5 ft.

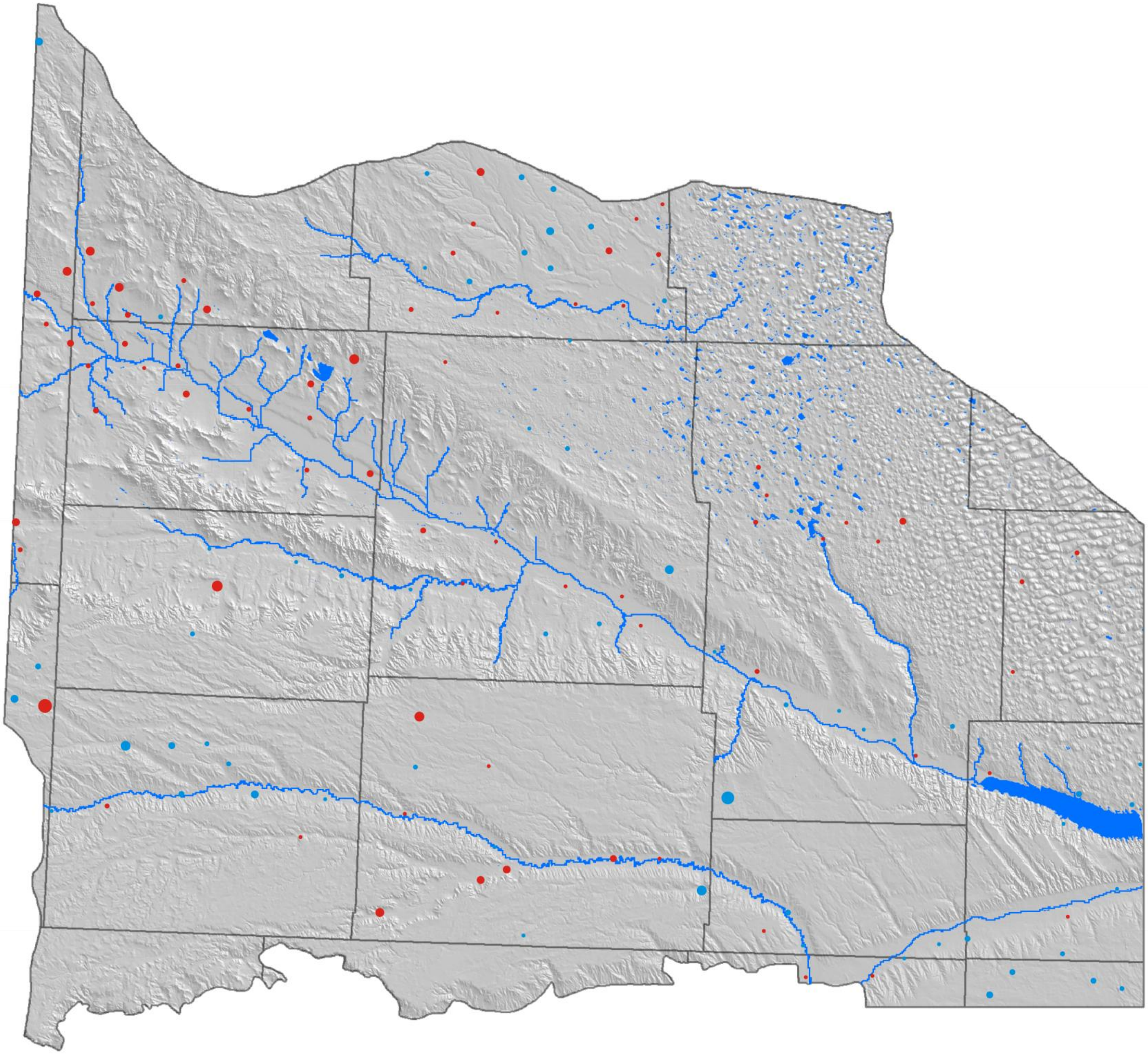


Figure 21. 1953-2011 mean residual at water-level targets. Negative residuals are red and positive residuals are cyan. Diameter of circle is proportional to absolute value of residual, except minimum diameter is maintained to aid in visibility.

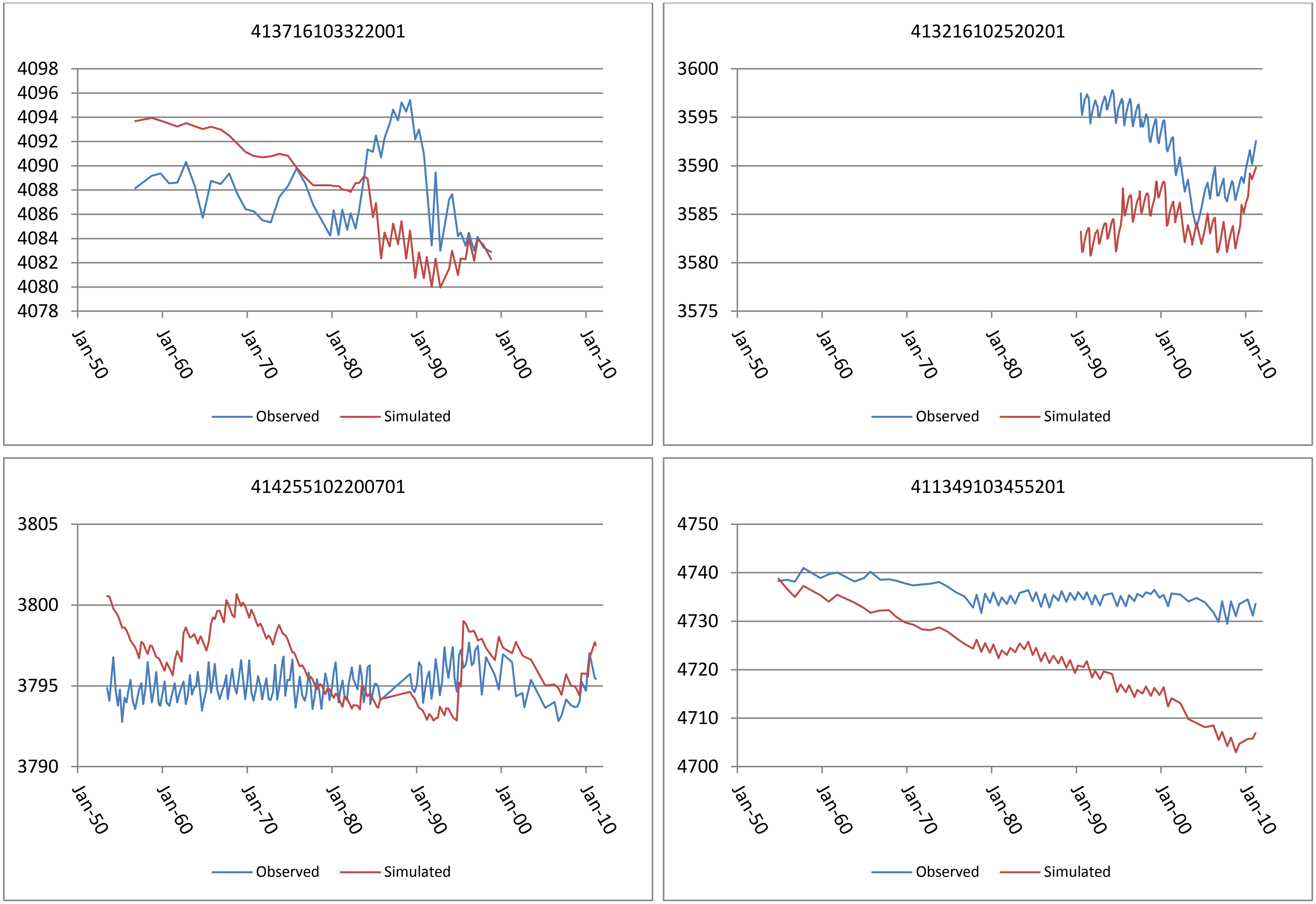


Figure 22. Simulated and observed water-level hydrographs for 1953-2011 at selected sites. Number above graph is U.S. Geological Survey Site ID.

1953-2011 Water-Level Change

Figure 23 shows simulated water-level change for 1953-2011. Simulated water-levels declines are as much as 138 ft in central Box Butte County and exceed 100 ft in a substantial part of the county. Simulated declines are as much as 53 ft in southern Keith County with declines exceeding 50 ft in a small area. Simulated declines exceed 25 ft in an area extending from Kimball County to Cheyenne County and another area extending from Morrill County into Garden County. There are simulated water-level rises, some exceeding 25 ft, across the southern part of the model. These may be due to simulated recharge on dryland. Elsewhere, simulated 1953-2011 water-level changes are small.

2005-06 Stream Baseflow

Table 8 shows simulated 2005-06 stream baseflow for selected streams in the model. The column "Fall simulated" represents simulated baseflow on October 31, 2005, and the column "Spring simulated" represents simulated baseflow on April 30, 2006. The targets represent estimated baseflow for those same months. Lodgepole Creek at Kimball, Brownson, and Sidney was not gaged during this time and the targets are based on miscellaneous measurements at various times at these sites. Jesse Bradley (Nebraska Department of Natural Resources) was not responsible for these targets.

The simulated baseflows for Horse Creek, Tub Springs Drain, Gering Drain, Ninemile Creek, and Red Willow Creek, tend to be higher than the target baseflows. The simulated baseflows for Dry Spottedtail Creek and Winters Creek tend to be lower than the target baseflows. The sum of the simulated fall baseflows for the north side tributaries to the North Platte River (shaded in the table) is higher than the target fall baseflows. For the fall, the sum of the simulated baseflows is greater than the sum of the targets by about 18 percent and in the spring, the sum is about 12 percent greater.

The simulated baseflow of Blue Creek is about 9 percent lower than the target in the fall and about 20 percent lower in the spring.

The simulated fall baseflows for Melbeta Drain, Indian Creek, Upper Dugout Creek, and Silvernail Drain are lower than the target baseflows. The simulated spring baseflows, except for Melbeta Drain, are higher than the target baseflows.

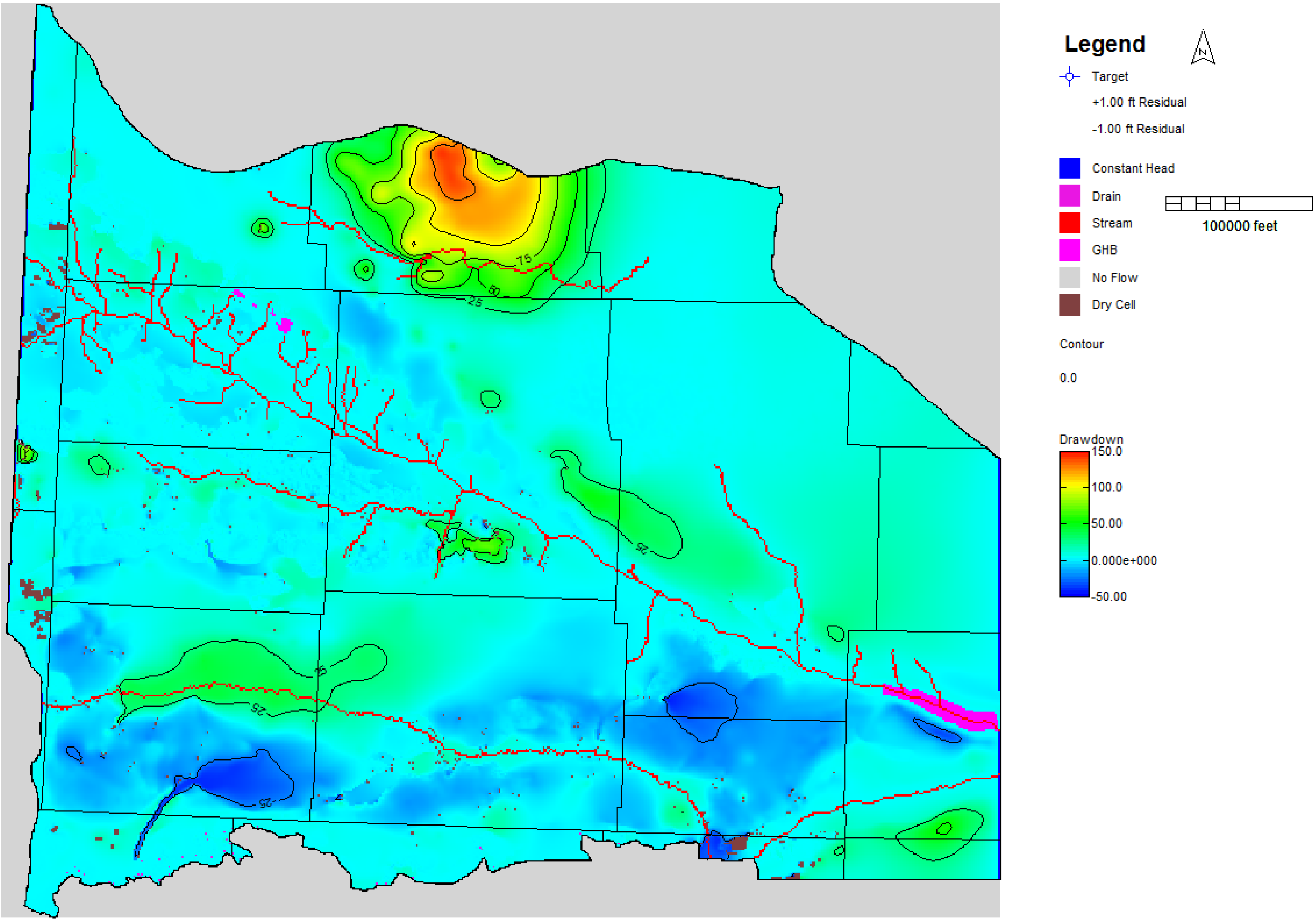


Figure 23. 1953-2011 simulated water-level change. Areas in white represent simulated dry cells in the model.

Table 8. Simulated 2005-06 stream baseflow for selected streams.

Stream	Fall Simulated	Spring Simulated	Fall Target	Spring Target
Kiowa Creek	31.3	29.2		
Horse Creek	64.2	54.9	19	9
Sheep Creek	39.9	34.8	41	34
Dry Spottedtail Creek	9.4	7.1	11	49
Tub Springs Drain	30.6	25.0	22	18
Winters Creek	18.7	14.7	37	24
Gering Drain	43.4	39.6	21	18
Ninemile Creek	67.3	55.6	44	29
Bayard Drain	14.3	8.0	16	5
Red Willow Creek	81.7	63.3	51	27
Pumpkin Creek	2.4	7.2	0	2
Sum of highlighted streams	262.0	208.6	222	187
Blue Creek	62.9	60.3	69	75
Otter Creek	4.7	4.6		
South Platte River	179.8	193.4		
North Platte River (Lewellen)	1,154	1,044		
Snake Creek	0.0	0.0		
Lodgepole (Bushnell)	10.4	10.6	12	14
Lodgepole Cr. (Kimball)	2.9	3.1	12	12
Lodgepole Cr. (Brownson)	6.0	6.2	2	2
Lodgepole Cr. (Sidney)	2.6	3.7	3	3
Lodgepole (Ralton)	0.4	0.5	7	9
Melbeta Drain	2.4	1.4	12	2
Indian Creek	11.5	10.9	30	5
Upper Dugout Creek	13.5	12.0	24	2
Slivernail Drain	4.8	4.0	18	4

1953-2011 Stream Baseflow Hydrographs

Figure 24 shows simulated and observed baseflow for selected streams for 1953-2011. Sheep Creek is the western-most north-side tributary to the North Platte River in Nebraska. The simulated baseflow to Sheep Creek is slightly lower than the observed baseflow and the simulated fall-to-spring amplitude in baseflow is less than observed. The simulated decrease in baseflow beginning in 2002 follows the observed decrease in baseflow nicely.

Dry Spottedtail Creek is the next north-side tributary to the North Platte River east of Sheep Creek. The streamflow record on Dry Spottedtail Creek begins in June 1961. The simulated baseflow to Dry Spottedtail creek is somewhat higher than the observed baseflow for the first half of the 1953-2011 period and then the simulated baseflow is about the same as the observed baseflow. The simulated fall-to-spring baseflow amplitude is about the same as the observed baseflow amplitude.

Gering Drain is a south-side tributary to the North Platte River in Scotts Bluff County. The simulated baseflow to Gering Drain is about 20 ft^3/s higher than the observed baseflow while the simulated fall-to-spring amplitude is much less than the observed amplitude. In general, the long term pattern of the of the simulated baseflows follows the pattern of the observed baseflow, especially early in the period.

Red Willow Creek is a north-side tributary to the North Platte River in western Morrill County. The simulated baseflow to Red Willow Creek is about 30 ft^3/s higher than the observed baseflow. However, the simulated fall-to-spring amplitude of baseflow is about the same as the observed amplitude and the long term pattern of the simulated baseflow is similar to the long term pattern of observed baseflow.

Pumpkin Creek is a south-side tributary to the North Platte River in central Morrill County. Pumpkin Creek drains a large valley in Banner, Scotts Bluff, and Morrill Counties. The flow of Pumpkin Creek has declined over time as ground-water development occurred in Pump Creek valley. The simulated baseflow to Pumpkin Creek is about the same as the observed baseflow and the simulated fall-to-spring amplitude is about the same as the observed amplitude. The simulated baseflow declines to about zero during the period as does the observed baseflow. The simulated baseflow rises late in the period, but this is after estimates of baseflow are available.

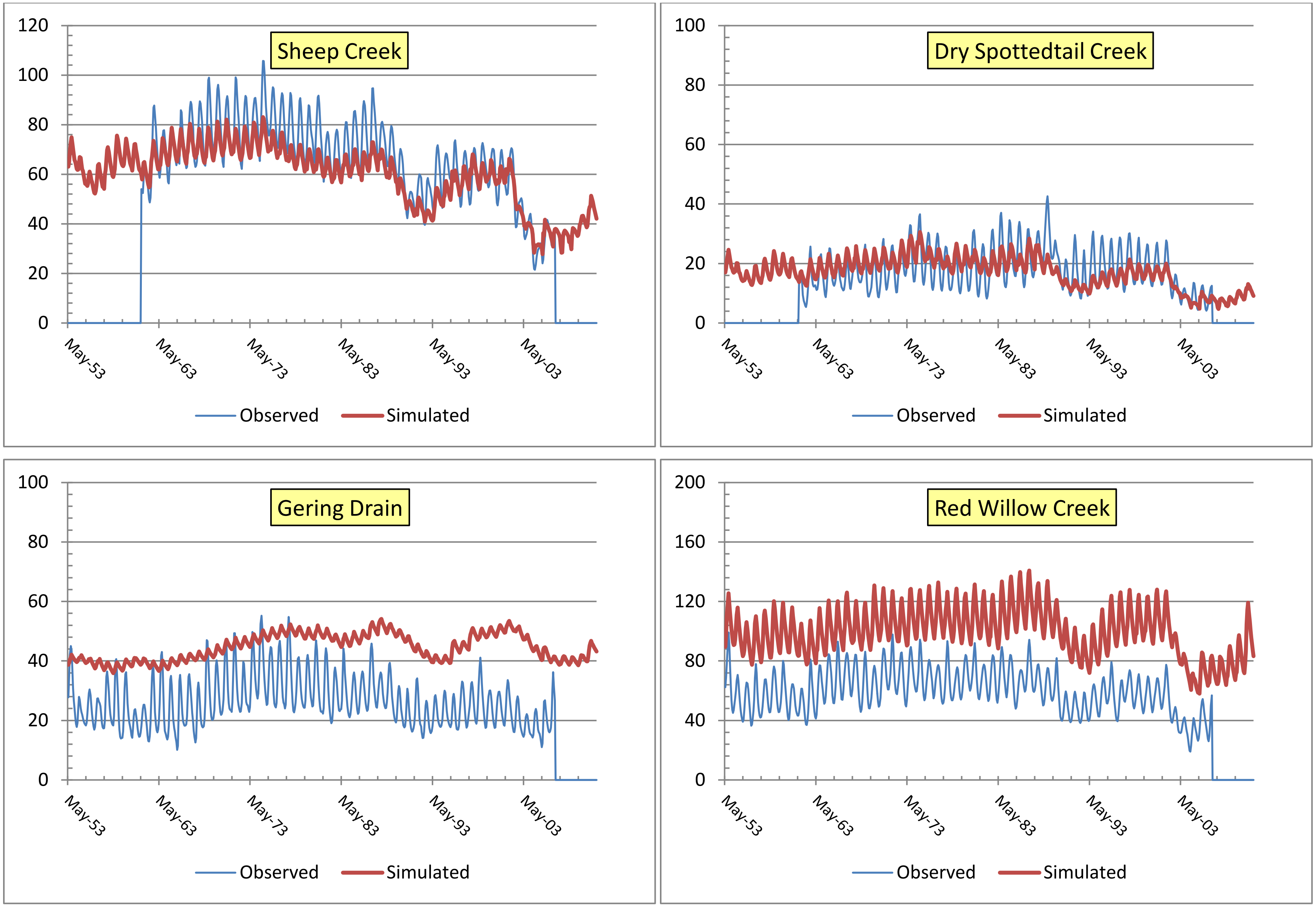


Figure 24. Simulated and observed stream baseflow hydrographs for 1953-2011 at selected sites. Zero values in observed at beginning and end are artifacts of the plotting routine.

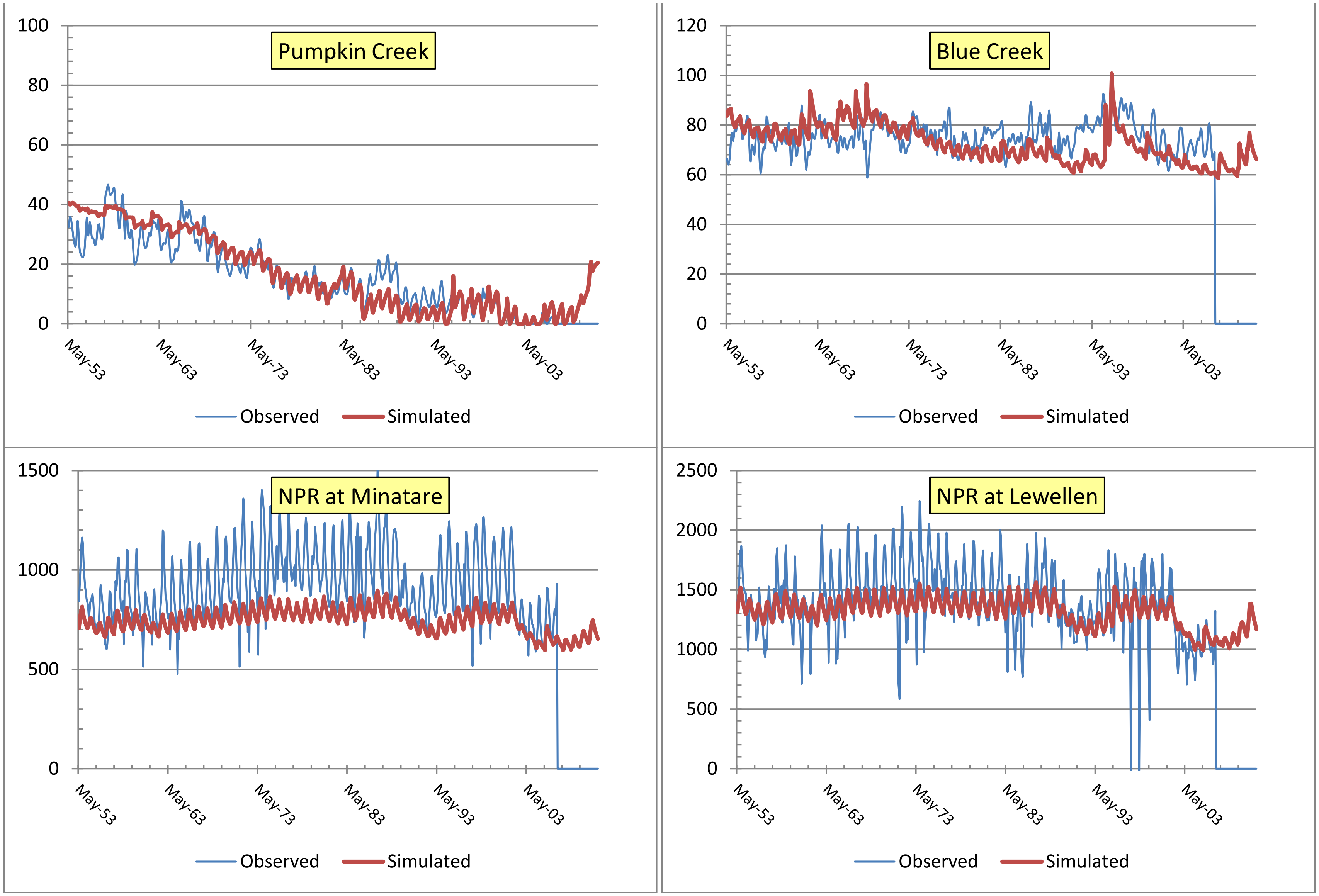


Figure 24 (continued). Simulated and observed stream baseflow hydrographs for 1953-2011 at selected sites. Zero values in observed at beginning and end are artifacts of the plotting routine.

Blue Creek is a north-side tributary to the North Platte River in Garden County. Blue Creek is below the bulk of the surface-water irrigation in the North Platte valley, although several small canals divert from this stream. Blue Creek tends to have very steady baseflow because it drains the Sand Hills. The simulated baseflow to Blue Creek is about the same as the observed baseflow, sometimes being above and sometimes being below. The simulated fall-to-spring amplitude is about the same as the observed amplitude. There is a gentle rise in the observed baseflow in the 1990s while there is an abrupt rise in the simulated baseflow in 1995. After 1995, both the observed baseflow and the simulate baseflow show a slight decline.

North Platte River (NPR) at Minatare is a main stem gage on the North Platte River in eastern Scotts Bluff County. The flow at this gage probably reflects the effects of less than half of the surface-water irrigation that occurs in the North Platte valley. The simulated baseflow at Minatare is about 180 ft^3/s less than the observed baseflow. The average simulated baseflow is 750 ft^3/s while the average observed baseflow is about 930 ft^3/s. The simulated fall-to-spring amplitude is slightly over 100 ft^3/s while the observed fall-to-spring amplitude approaches 500 ft^3/s. Estimating baseflow for the North Platte River is very difficult, so the observed values need to be taken with a grain of salt.

North Platte River (NPR) at Lewellen is a main stem gage on the North Platte River in eastern Garden County. The flow at this gage probably reflects most of what is happening in the North Platte valley in the study area. The flows at Lewellen are greater than the flows at Minatare, but the patterns are similar. The simulated baseflow at Lewellen is about 30 ft^3/s greater than the observed baseflow. The average simulated baseflow is 1,320 ft^3/s while the average observed baseflow is about 1,290 ft^3/s. The simulated fall-to-spring amplitude is slightly less than 200 ft^3/s while the observed fall-to-spring amplitude is nearly 1,000 ft^3/s. It is encouraging that both the simulated and observed baseflow at Lewellen show a similar decline in the early 2000s.

2010-11 Water Budgets

Table 9 shows simulated water budgets for 2010-11 for various subregions of the study area. These are the same subregions shown in the Pre-Ground-water Development Period Calibration section. The sign convention for the table is that negative indicates water entering the aquifer in the subregion and positive indicates water leaving the aquifer. Therefore, "Wells" are positive because they represent water leaving the aquifer.

Table 9. Simulated water budgets for 2010-11 by subregion. Units are acre-feet per year, except for area, which is acres. Negative values indicate water entering aquifer. Values, except for error, are rounded to nearest 100.

Zone	Area	Recharge	Constant head boundary	Springs	Lakes	Wells	Streams	ET	Outflow from subregion	Storage decrease	Error
1	274,200	-24,400	0	0	0	2,700	1,200	800	10,700	9,000	0
2	417,600	-179,200	0	0	0	17,000	0	26,900	38,100	97,200	0
3	661,000	-215,600	0	0	0	10,800	0	71,700	60,800	72,300	0
4	189,400	-95,400	0	0	0	2,100	3,800	100	70,700	18,600	0
5	478,400	-86,000	0	0	0	18,700	13,900	4,100	-2,100	51,400	0
6	141,600	-13,700	0	0	0	6,700	0	0	6,800	200	0
7	416,100	-377,200	0	0	1,800	49,500	349,700	5,100	-93,800	64,900	0
8	292,900	-281,900	0	0	0	26,200	202,900	9,000	-28,300	72,000	0
9	288,200	-60,100	0	0	0	18,300	114,500	3,500	-78,700	2,400	0
10	191,600	-40,200	0	0	0	5,000	2,100	0	8,300	24,700	0
11	219,300	-20,200	0	0	0	12,500	0	0	6,000	1,700	0
12	312,600	-21,400	0	0	0	2,800	0	0	11,100	7,500	0
13	424,100	-84,100	0	0	0	27,000	0	0	17,000	40,200	-1
14	196,400	-22,200	0	0	0	3,100	0	0	9,000	10,000	0
15	212,800	-34,300	0	0	0	5,000	0	0	4,100	25,200	0
16	28,600	-1,500	0	0	0	1,400	-1,400	0	300	1,300	0
17	59,200	-6,400	0	0	0	13,000	-2,700	0	-6,700	2,800	0
18	85,800	-5,000	0	0	0	4,000	2,200	0	-5,800	4,600	0
19	76,300	-6,100	0	0	0	7,200	2,000	0	-7,600	4,500	0
20	35,100	-9,900	0	0	0	9,200	-600	200	800	300	0
21	698,100	-217,700	0	0	0	173,400	800	44,400	-23,500	22,600	0
22	743,500	-124,500	47,100	0	37,700	44,600	1,800	13,100	-22,300	2,500	-3
23	362,400	-21,500	0	2,800	0	8,600	5,300	200	3,600	1,000	0
24	305,600	-61,000	-4,200	0	0	12,800	19,800	1,200	21,400	9,900	0
Sum	**7,110,800**	**-2,009,500**	**42,900**	**2,800**	**39,500**	**481,600**	**715,300**	**180,300**	**-100**	**546,800**	**-4**

Not all water-budget components exist for all subregions. For example, "Lakes" only exist in subregions 7 (Scotts Bluff-Sioux Overappropriated Area) and subregion 22 (Twin Platte and Upper Loup Natural Resources Districts). These represent Inland Lakes and Lake McConaughy respectively.

Error represents the error in the water budget and it was calculated before the other values in the table were rounded. The largest error, -3 acre-feet, occurred in subregion 22 (Twin Platte and Upper Loup Natural Resources District). This error is 0.002 percent of the water budget for this subregion. The next largest error, -1 acre-feet, occurred in subregion 23 (Colorado) and is 0.001 percent of the water budget for this subregion.

Summary

This report documents a ground-water flow model of 11,100 mi^2 of the southern two-thirds of the Nebraska Panhandle. The study area extends from the limit of the High Plains aquifer on the south to ground-water divides and flow lines on the north and from 6 mi into Wyoming on the west to the dam on Lake McConaughy on the east. Ground water generally flows from west to east in the study area, and more locally flows to streams that drain the area. Geologic units that make up the High Plains aquifer include the fractured Brule Formation, Arikaree Group, Ogallala Group, Broadwater Formation, and various sediments of Quaternary age.

Saturated thickness in the study area ranges from essentially zero to over 800 ft. The largest saturated thickness occurs beneath the Sand Hills in the northeastern part of the study area. Elsewhere, saturated thickness is quite variable, and in places is controlled by paleovalleys.

Prior to settlement, recharge occurred because of precipitation on rangeland. This recharge ranged from less than 0.20 in/yr on the tablelands in the southwestern part of the study area to more than 2.4 in/yr in the Sand Hills in the northeastern part. Beginning in the late 1800s, canals were used to irrigate land and this caused additional recharge.

The primary natural discharge from the aquifer was baseflow to streams and rivers that drain the area. Prior to development of the surface-water system, most of the discharge occurred to the North Platte River and its western tributaries had little flow. In the east, Blue Creek received substantial discharge from the aquifer. A secondary mechanism for discharge from the aquifer was evapotranspiration where the water table was near land surface. The largest such area is in the Sand Hills in northern Garden County and southern Sheridan County where there are numerous lakes. There also is evapotranspiration from the riparian forests along the North Platte River and South Platte River. Beginning in about the 1950s, pumpage for irrigation became a substantial artificial discharge from the aquifer.

The history of the ground-water flow system was broken into three periods: the pre-canal period before the late 1800s, the pre-ground-water development period before the early 1950s, and the ground-water development period after the early 1950s. In the model, the first period ended in 1895, the second period ended in 1953, and the third period ended in 2011.

MODFLOW-2000 was selected as the ground-water flow modeling code for this study. The code uses block-centered finite-difference techniques to solve the ground-water flow equation at numerous points throughout the study area. The study area was divided into 177,780 cells of 40 acres each in the model. The pre-canal period was simulated using a 2,000-year period with time steps of 5 or 10 days. The pre-ground-water period was simulated with 5-day time steps for an irrigation period and a non-irrigation period each year. The ground-water development period was simulated using 5-day time steps for monthly periods.

The external boundaries of the model included lateral fixed head (water-level) boundaries, lower no-flow boundaries at the base of the aquifer, and the simulated water table. Internal boundaries of the model included streams, lakes, springs, and evapotranspiration areas.

Two aquifer properties were estimated during calibration of the model: hydraulic conductivity and specific yield. Hydraulic conductivity, which describes the flow through the aquifer under laboratory conditions, ranged from 7 ft/d in part of the Arikaree Formation to 150 ft/d in part of the Quaternary age alluvium. Specific yield, which describes release of water from storage in the aquifer, ranged from 0.135 to 0.15 (dimensionless).

Other model inputs adjusted during model calibration included streambed conductance and paleovalleys. Streambed conductance, which is one parameter that controls stream-aquifer interaction, ranged from 1.0 ft/d per foot of length to 20 ft/d per foot of length in the calibrated model. Paleovalleys were used to adjust both base of aquifer and hydraulic conductivity. Within paleovalleys, base of aquifer was lowered 200 ft and hydraulic conductivity was increased to 120 ft/d.

Two aquifer stress, recharge and pumpage, were estimated in concurrent studies and were provided to this study. These stresses were not changed during model calibration. Other model inputs were set during model construction and were not changed during model calibration.

Simulated 1953 water levels at 297 targets ranged from 100 ft below observed values to 86 ft above observed values. The weighted average difference was -2.9 ft and the unweighted average difference was -7.2 ft. The weighted mean absolute difference was 7.2 ft and the unweighted mean absolute difference was 20.6 ft.

Simulated fall 1952 baseflow for north side tributaries to the North Platte River above Pumpkin Creek was about the same as observed baseflow. Simulated spring 1953 baseflow for the same tributaries was 19 percent greater than observed baseflow.

The largest simulated inflow component of the 1952-53 water budget was recharge and the largest outflow component was streamflow. The overall error in the water budget was 546 acre-feet, compared to overall recharge of 1,197,000 acre-feet.

Simulated 2010-11 water levels at 85 targets ranged from 71 ft below observed values to 94 ft above observed values. The average difference was +2.5 ft. For 1953-2011, there were 8,290 targets at 131 sites. The weighted average difference was -2.5 ft and the unweighted average difference was -4.6 ft. The weighted mean absolute difference was 10.0 ft and the unweighted mean absolute difference was 17.0 ft.

Simulated fall 2010 baseflow for north side tributaries to the North Platte River above Pumpkin Creek was about 18 percent greater than observed baseflow. Simulated spring 2011 baseflow for the same tributaries was 12 percent greater than observed baseflow. The average simulated 1953-2011 baseflow to the North Platte River at Lewellen was about 1,320 ft^3/s while the average observed baseflow was about 1,290 ft^3/s.

The largest simulated inflow component of the 2010-11 water budget was recharge and the largest outflow components were streamflow, pumpage, and decrease in storage. The overall error in the water budget was 4 acre-feet, compared to overall recharge of 2,009,500 acre-feet.

References Cited

Ayers, J.F., 2007, Box Butte County - Niobrara River Groundwater Flow Model: Conservation and Survey Division, University of Nebraska–Lincoln, 116 p.

Ball, L.B., Kress, W.H., Steele, G.V., Cannia, J.C., and Anderson, M.J., 2006. Determination of canal leakage potential using continuously resistivity profiling techniques, Interstate and Tri-State Canals, western Nebraska and eastern Wyoming, 2004: U.S. Geological Survey Scientific Investigations Report 2006-5032, 59 p.

Bishop-Brogden Associates, Inc., 2002. North Platte River return flow study and model: Biship-Brogden Associates, Inc., 127 p. plus 10 appendices.

Babcock, H.M., and Visher, F.N., 1951, Ground-water conditions in the Dutch Flats area, Scotts Bluff and Sioux Counties, Nebraska, *with a section on* Chemical quality of ground water, by W.H. Duram: U.S. Geological Survey Circular 126, 51 p.

Babcock, H.M., and Visher, F.N., 1952, Reconnaissance of the geology and ground-water resources of the Pumpkin Creek area, Morrill and Banner Counties, Nebraska, *with a section on* Chemical quality of the water, by W.H. Durum: U.S. Geological Survey Circular 156, 30 p.

Bjorklund, L.J., 1957, Geology and ground-water resources of the lower Lodgepole Creek drainage basin, Nebraska, *with a section on* Chemical quality of the water by E.R. Jochens: U.S. Geological Survey Water-Supply Paper 1410, 76 p.

Bjorklund, L.J., and Brown, R.F., 1957, Geology and ground-water resources of the lower South Platte River valley between Hardin, Colorado, and Paxton, Nebraska, *with a section on* Chemical quality of the ground water, by H.A. Swenson: U.S. Geological Survey Water-Supply Paper 1378, 431 p.

Burton, B.L., Johnson, M.R., Vrabel, Joseph, Imig, B.H., Payne, J.D., and Tompkins, R.E., 2009. Capacitively coupled resistivity surveys of selected irrigation canals within the North Platte River valley, western Nebraska and eastern Wyoming, 2004 and 2007-2009: U.S. Geological Survey Scientific Investigations Report 2009-5194, 70 p.

Cady, R.C., and Scherer, O.J., 1946, Geology and ground-water resources of Box Butte County, Nebraska: U.S. Geological Survey Water-Supply Paper 969, 102 p.

Condon, S.M., 2005, Geologic studies of the Platte River, south-central Nebraska and adjacent areas - Geologic maps, subsurface study, and geologic history: U.S. Geological Survey Professional Paper 1706, 63 p.

Conservation and Survey Division, 1998, The groundwater atlas of Nebraska: Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln: Resource Atlas No. 4a/1998, 44 p.

Dappen, Patti, and Merchant, Jim, 2003, Delineation of 2001 land use patterns for the Cooperative Hydrology Study in the central Platte River basin: Center for Advanced Land Management Information Technologies (CALMIT), Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 83 p.

Dappen, Patti, and Merchant, Jim, 2004, Delineation of 1982 land use patterns for the Cooperative Hydrology Study in the central Platte River basin: Center for Advanced Land Management Information Technologies (CALMIT), Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 84 p.

Dappen, Patti, and Tooze, Marcus, 2001, Delineation of land use patterns for the Cooperative Hydrology Study in the central Platte River Basin: Center for Advanced Land Management Information Technologies (CALMIT), Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 73 p.

Dappen, Patti, Merchant, Jim, Ratcliffe, Ian, and Robbins, Cullen, 2006, Delineation of 2005 land use patterns for the state of Nebraska Department of Natural Resources in the central Platte River basin: Center for Advanced Land Management Information Technologies (CALMIT), Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 87 p.

Darton, N.H., 1899, Preliminary report on the geology and water resources of Nebraska west of the one hundred and third meridian: U.S. Geological Survey 19th Annual Report, Part IV, p. 719-814

Darton, N.H., 1903, Preliminary report on the geology and water resources of Nebraska west of the one hundred and third meridian: U.S. Geological Survey Professional Paper 17, 69 p.

Darton, N.H., 1905, Preliminary report on the geology and underground water resources of the central Great Plains: U.S. Geological Survey Professional Paper 32, 433 p.

Diffendal, R.F., Jr., 1999, Deuel County test-hole logs: Nebraska Water Survey Test-Hole Report No. 25, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 93 p.

Diffendal, R.F., Jr., 2000, Cheyenne County test-hole logs: Nebraska Water Survey Test-Hole Report No. 17, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 243 p.

Diffendal, R.F., Jr., and Goeke, J.W., 2000, Arthur County test-hole logs: Nebraska Water Survey Test-Hole Report No. 3, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 56 p.

Diffendal, R.F., Jr., and Goeke, J.W., 2004, Keith County test-hole logs: Nebraska Water Survey Test-Hole Report No. 51, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 121 p.

Dreeszen, V.H., 2000, Perkins County test-hole logs: Nebraska Water Survey Test-Hole Report No. 68, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 112 p.

Dugan, Jack T., and Zelt, Ronald B., 2000. Simulation and analysis of soil-water conditions in the Great Plains and adjacent areas, 1951-80: U.S. Geological Survey Water-Supply Paper 2427, 81 p.

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R., and Weeks, J.B., 1984. Geohydrology of the High Plains aquifer in parts of Colorado, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-B, 63 p.

Harbaugh, A.W., and McDonald, M.G., 1996, User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-485, 56 p.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water flow model – User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Kress, W.H., Dietsch, B.J., Steele, G.V., White, E.A., and Cannia, J.C., 2004, Use of continuous seismic profiling to differentiate geologic deposits underlying selected canals in central and western Nebraska: U.S. Geological Survey Fact Sheet 115-03, 6 p.

Lappala, E.G., Emery, P.A., and Otradovsky, F.J., 1979, Simulated changes in ground-water levels and streamflow resulting from future development (1970-2020) in the Platte River Basin: U.S. Geological Survey Water-Resources Investigations Report 79-26, 82 p.

Luckey, R.R., and Cannia, J.C., 2006. Groundwater flow model of the western model unit of the Nebraska Cooperative Hydrology Study (COHYST) area: Cooperative Hydrology Study, 63 p.

Luckey, R.R., Carney, C.P., and Peterson, S.M., 2001. Estimated groundwater discharge to streams from the High Plains aquifer in the western model unit of the Cooperative Hydrology Study area for the period prior to major groundwater irrigation: Cooperative Hydrology Study, 20 p.

Luckey, R.R., Gutentag, E.D., Heimes, F.J., and Weeks, J.B., 1986, Digital simulation of ground-water flow in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-D, 57 p.

Martin, Derrel, 2000, Post-decree changes in the water supply and irrigation development in the North Platte River valley from Whalen, Wyoming to Lewellen, Nebraska: Unpublished report in files of Nebraska Department of Natural Resources.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, Chapter A1, Book 6, 586 p.

McLean, J.S., Chen, H.H., and Goeke, J.W., 1997, Simulation of ground-water flow in the High Plains aquifer, southern sandhills area, west-central Nebraska: U.S. Geological Survey Open-File Report 96-206, 16 p.

Meinzer, O.E., 1917, Ground water for irrigation in Lodgepole Valley, Wyoming and Nebraska: U.S. Geological Survey Water-Supply Paper 425-B, 33 p.

Missouri Basin States Association, 1982a, Technical Paper, Ground Water Depletion, Platte and Kansas River Basins, Colorado-Kansas-Nebraska-Wyoming, Appendix II of Ground Water Depletions Technical Paper; Omaha, Nebr., Missouri River Basin Hydrology Study, 71 p.

Missouri Basin States Association, 1982b, Transmissivity and stream depletion factor maps; Platte and Kansas River Basins, Colorado-Kansas-Nebraska-Wyoming, Appendix II of Ground Water Depletions Technical Paper; Omaha, Nebr., Missouri River Basin Hydrology Study, 16 pls.

Missouri River Basin Commission, 1975, Stream-aquifer hydrology, technical paper, Platte River Basin, Nebraska, Level B Study: Missouri River Basin Commission, 67 p.

Nace, R.L., 1953, Ground water for irrigation in Box Butte County, Nebraska, *with a section on* Chemical quality of water by W.H. Durum: U.S. Geologcial Survey Circular 166, 39 p.

Nebraska Department of Natural Resources, 2009, 2009 Hydrographic Report: Nebraska Department of Natural Resources, 230 p.

Peterson, S.M., Stanton, J.S., Saunders, A.T., and Bradley, J.R., 2008, Simulation of ground-water flow and effects of ground-water irrigation on base flow in the Elkhorn and Loup River Basins, Nebraska: U.S. Geological Survey Scientific Investigations Report 2008–5143, 65 p.

Pettijohn, R.A., and Chen, H.H., 1983a, Geohydrology of the High Plains aquifer system in Nebraska: U.S. Geological Survey Water-Resources Investigations Report 82-502, map, scale 1:175,000, 3 sheets.

Pettijohn, R.A., and Chen, H.H., 1983b, Hydraulic conductivity, specific yield, and pumpage--High Plains aquifer system, Nebraska: U.S. Geological Survey Water-Resources Investigations Report 82-4014, map, scale 1:175,000, 3 sheets.

Pettijohn, R.A., and Chen, H.H., 1984, Hydrologic analysis of the High Plains aquifer system in Box Butte County, Nebraska: U.S. Geological Survey Water-Resources Investigations Report 84-4046, 54 p.

Sibray, S.S., and Smith, F.A., 2000, Scotts Bluff County test-hole logs: Nebraska Water Survey Test-Hole Report No. 79, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 49 p.

Smith, F.A., 1969, Preliminary groundwater report, Cheyenne County, Nebraska: Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, MP-7, 100 p.

Smith, F.A., 2000a, Banner County test-hole logs: Nebraska Water Survey Test-Hole Report No. 4, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 47 p.

Smith, F.A., 2000b, Box Butte County test-hole logs: Nebraska Water Survey Test-Hole Report No. 7, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 84 p.

Smith, F.A., 2000c, Kimball County test-hole logs: Nebraska Water Survey Test-Hole Report No. 53, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 153 p.

Smith, F.A., and Souders, V.L., 1971, Occurrence of groundwater in Kimball County, Nebraska, including logs of test holes: Nebraska Water Supply Paper 29, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 135 p.

Smith, F.A., and Souders, V.L., 1975, Groundwater geology of Banner County, Nebraska: Nebraska Water Supply Paper 39, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 96 p.

Smith, F.A., and Swinehart, J.B., 2000, Garden County test-hole logs: Nebraska Water Survey Test-Hole Report No. 35, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 91 p.

Souders, V. L., Smith, F. A., and Swinehart, J. B., 1980, Geology and groundwater supplies of Box Butte County, Nebraska: Nebraska Water Supply Paper 47, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 205 p.

Souders, V.L., and Swinehart, J.B., 2000, Morrill County test-hole logs: Nebraska Water Survey Test-Hole Report No. 62, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska–Lincoln, 106 p.

Stanton, J.S., Peterson, S.M., and Fienen, M.N., 2010, Simulation of groundwater flow and effects of groundwater irrigation on stream base flow in the Elkhorn and Loup River Basins, Nebraska, 1895–2055—Phase two: U.S. Geological Survey Scientific Investigations Report 2010–5149, 78 p.

Stanton, J.S., Qi, S.L., Ryter, D.W., Falk, S.E., Houston, N.A., Peterson, S.M., Westenbroek, S.M., and Christenson, S.C., 2011, Selected approaches to estimate water-budget components of the High Plains, 1940 through 1949 and 2000 through 2009: U.S. Geological Survey Scientific Investigations Report 2011–5183, 79 p.

Steele, G.V., Cannia, J.C., and Scripter, K.G., 2002, Hydrologic characteristics of selected alluvial aquifer in the North Platte Natural Resources District, western Nebraska: U.S. Geological Survey Water-Resources Investigations Report 01-4241, 24 p.

Steele, G.V., Cannia, J.C., and Stanton, J.S. 1998, Geohydrology and water quality of the North Platte River alluvial aquifer, Garden County, western Nebraska, 1993-94: U.S. Geological Survey Water-Resources Investigations Report 98-4033, 75 p.

Swinehart, J.B., and Diffendal, R.F., Jr., 1997, Geologic map of the Scottsbluff 1º x 2º quadrangle, Nebraska and Colorado: U.S. Geological Survey Geologic Investigations Series Map I-2545, 1 sheet, scale 1:250,000.

Swinehart, J.B., Souders, V.L., DeGraw, H.M., and Diffendal, R.F., Jr., 1985, Cenozoic paleogeography of western Nebraska, *in* Flores, R.M., and Kaplan, S.S., eds., Cenozoic paleogeography of the west-central United States: Society of Economic Paleontologists and Mineralogists, Rocky Mountain section, Rocky Mountain Paleogeography Symposium 3, Denver, 1985, p. 209-229.

Swinehart, J.b., Dreeszen, V.H., Richmond, G.M., Tipton, M.J., Bretz, R., Steele, F.V., Hallenberg, G.R., and Goebel, J.E., compilers, 1994, Quaternary geologic map of the Platte River 4°X6° quadrangle, United States: U.S. Geological Survey Miscellaneous Investigations Series Map I-1420 (NK-14), scale 1:1,000,000.

U.S. Bureau of Reclamation, 2012. HYDROMET Data System: Accessed April 5, 2012 at URL http://www.usbr.gov/gp/hydromet/ .

U.S. Geological Survey, 2010. National Hydrography Dataset: Accessed November 10, 2010 at URL http://nhd.usgs.gov/ .

U.S. Geological Survey, 2011. Seamless Data Warehouse: Accessed September 16, 2011 at URL http://seamless.usgs.gov/ned1.php/ .

Verstraeten, I.M., Steele, G.V., Cannia, J.C., Hitch, D.E., Scripter, K.G., Böhlke, J.K., Kraemer, T.F., and Stranton, J.S., 2001, Interaction of surface water and ground water in the Dutch Flats area, western Nebraska, 1995-99: U.S. Geological Survey Water-Resources Investigations Report 01-4070, 56 p.

Vrabel, Joseph, Teeple, A.P., and Kress, W.H., 2009. Estimation of leakage potential of selected sites in Interstate and Tri-State Canals using geostatistical analysis of selected capacitively coupled resistivity profiles, western Nebraska: U.S. Geological Survey Scientific Investigations Report 2009-5223, 24 p.

Weeks, J.B., Gutentag, E.D., Heimes, F.J., and Luckey, R.R., 1988, Summary of the High Plains regional aquifer-system analysis in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Professional Paper 1400-A, 30 p.

Wenzel, L.K., Cady, R.C., and Waite, H.A., 1946, Geology and ground-water resources of Scotts Bluff County, Nebraska: U.S. Geological Survey Water-Supply paper 943, 150 p.